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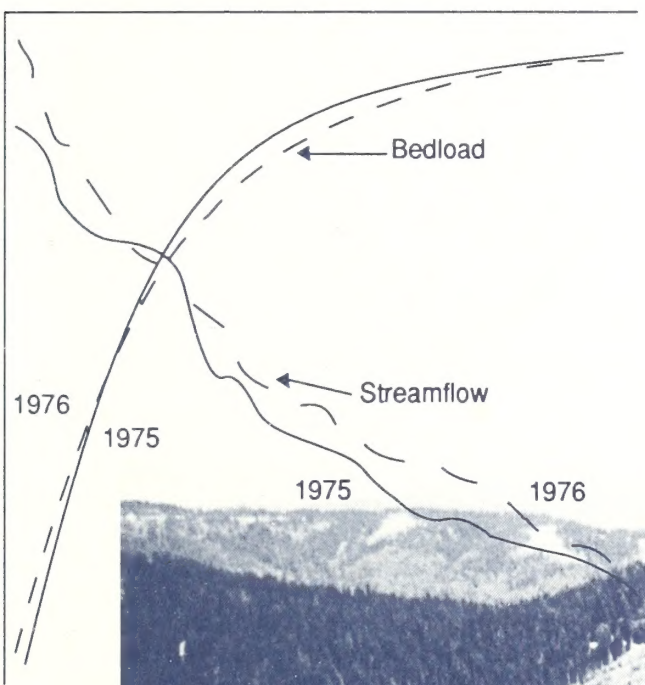
Streamflow Responses to Road Building and Harvesting: a Comparison With the Equivalent Clearcut Area Procedure

John G. King



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RESEARCH SUMMARY

Streamflow responses to timber removal by road building and patch clearcutting in four small, south-aspect watersheds in northern Idaho are compared to predicted responses using the equivalent clearcut area (ECA) procedure. The ECA procedure overestimated average annual water yield prior to timber removal by about 4.5 inches (10 percent). Increases in average annual water yield on the areas in equivalent clearcut condition were substantially higher than predicted. The relationship between elevation and annual water yield increase used in the ECA procedure estimated about a 37 percent increase in onsite annual water yield compared to observed increases ranging from 51.2 to 80.1 percent for an average water year. The results emphasize the need to have reliable local precipitation and streamflow records to calibrate relationships in the ECA procedure. The relationships developed at the Horse Creek site may be applicable to many northern Idaho sites if local relationships have not been developed.

Timber cutting guidelines used in the ECA procedure often place limits on expected increases in the maximum monthly streamflow during spring snowmelt. This limit is to prevent increases in high streamflows that potentially could damage or alter the channel. In the small Horse Creek watersheds, high streamflows of relatively short duration, about the 7 or 8 days of highest flow, are responsible for the majority of bedload sediment transport and have the potential to modify the channel. Limits on expected increases in instantaneous peak or maximum daily streamflows would be more appropriate for providing channel protection than limits on maximum monthly streamflow increases, especially for first and second order streams.

The ECA procedure currently estimates streamflow responses in third to fifth order watersheds and does not directly consider hydrologic responses in smaller headwater streams. Relatively large increases in instantaneous peak and maximum daily streamflows following timber removal occurred in the first and second order Horse Creek watersheds. Consideration of hydrologic responses in small watersheds should be incorporated into predictive procedures, especially in stream systems that may be sensitive to increases in high streamflows.

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Streamflow Responses to Road Building and Harvesting: a Comparison With the Equivalent Clearcut Area Procedure

John G. King

INTRODUCTION

Many National Forest hydrologists in the Northern Region use some adaptation of the equivalent clearcut area (ECA) procedure to forecast average streamflow responses to vegetation removal by timber harvesting, road building, and fire. This procedure is used to estimate the effects of past activities on streamflow and to develop a schedule of entry for future activities that manipulate vegetation in third to fifth order watersheds. Each hydrologist, in conjunction with other resource specialists, develops guidelines that set limits on the expected increases in certain streamflow variables. For example, the Idaho Panhandle National Forests (USDA FS 1977) have timber cutting guidelines that (1) limit the increase in mean annual streamflow to 10 percent, which may be adjusted depending on channel stability or soil characteristics or both,(2) limit the increase in the highest monthly yield to 20 percent, and (3) limit the increase in the channel impact period to 20 percent. The channel impact period is that time during which streamflow exceeds 75 percent of the highest average monthly streamflow for undisturbed conditions. Inherent in these guidelines is the assumption that increases in high flows or the duration of high flows may accelerate channel erosion and that certain channel characteristics can be evaluated to define the ability of the channel to safely handle increases in streamflow. The application of this procedure and guidelines provides a means of comparing different management options for a watershed and of estimating the amount of timber that can be removed from a watershed over a given period. It is one of many tools used by the hydrologists, in addition to their professional judgment, to aid in making land management decisions.

This procedure was based on the best available information at the time it was developed. Different versions of this procedure now exist mainly to reflect local conditions. Many of the relationships used in the various forms of this procedure are based on limited local data or data extrapolated from other geographical areas. Thus, as additional knowledge becomes available on streamflow modification following management activities, the relationships within the procedure should be modified for those geographic areas to which the data are applicable.

Currently there are 5 years of streamflow data following road building and harvesting available from four of the Horse Creek administrative-research watersheds in north-central Idaho. In addition, there are 4 or 5 years of streamflow and precipitation data for 11 watersheds prior to any new road building or harvesting and 10 to 12 years of data from four undisturbed watersheds. These data were used to develop several of the relationships in the ECA procedure for comparison with some of the currently used relationships for the purpose of calibrating the model and improving its reliability and usefulness.

The ECA procedure was first published in "Forest Hydrology Part II: Hydrologic Effects of Vegetation Manipulation" (USDA FS 1974). Although many forms of this procedure exist, the basic procedural steps remain the same. Average annual water yields for undisturbed forest conditions are estimated for the different elevation zones, and average annual water yield for the watershed is determined by summing the area-weighted yield from each elevation zone. Because there is greater availability of precipitation data, a relationship between average annual precipitation and average annual water yield is often used to estimate water yield. Local precipitation data are used to estimate average annual precipitation for the elevation zones within a watershed. The Horse Creek data will be compared with the relationship between average annual precipitation and water yield developed by the Soil Conservation Service (SCS) (Farnes 1972) for mountain watersheds in Montana and commonly used in the ECA procedure.

The next step in the ECA procedure is to estimate the increase in the average annual water yield by elevation zone following vegetation removal. Roads, clearcuts, burned areas, and partial cuts are all expressed as "equivalent clearcut areas," hence the name of the procedure. For example, a 100-acre partial cut where 40 percent of the crown area is removed would be equated to a 25-acre clearcut, a smaller area than the 100 acres on which the activity occurred (USDA FS 1974, p. 39). The increase in average annual water yield on an equivalent clearcut area is estimated as a function of elevation. However, some National Forest hydrologists also incorporate land type or soils information that modifies this elevation versus water yield increase function. The Horse

Creek data will be used to compare with one of the commonly used elevation versus water yield increase relationships (USDA FS 1974, p. 41).

In the ECA procedure the increase in annual water yield is distributed by month over the snowmelt season as a function of general aspect and elevation of the equivalent clearcut areas. This distribution of the annual water yield is done to allow estimation of the increases in the highest monthly yield and the channel impact period. The channel impact period is the time during which streamflow exceeds 75 percent of the maximum average monthly streamflow. The harvesting-induced responses in several variables that describe high streamflows during the spring snowmelt period will be evaluated using data from the Horse Creek watersheds. This analysis will be used to describe the peakflow responses for small south-facing watersheds. These results cannot be used to improve any relationship in the ECA procedure because the procedure is usually applied to much larger watersheds. However, the results are useful in demonstrating which peakflow variable best reflects flows that have the potential to alter the channel.

The ECA model also incorporates a relationship that allows the user to estimate reductions in the initial water yield increase over time as vegetation regrows. This relationship, modified by habitat type, cannot be evaluated with only 5 years of data following harvesting in the Horse Creek watersheds.

STUDY SITE

The Horse Creek administrative-research site is in the Nez Perce National Forest in north-central Idaho, about 35 miles east of Grangeville. Two third order streams, the Main and East Forks of Horse Creek, drain the area toward the east, entering Meadow Creek several miles upstream from its confluence with the Selway River. Within the Main Fork basin are 15 gauged first and second order watersheds, 10 on the north side of the Main Fork and five on the south side (fig. 1). One watershed on each side of the Main Fork serves as an undisturbed control watershed. Roads have been constructed in 11 of the watersheds, and portions of four of these watersheds with roads have also been partially harvested.

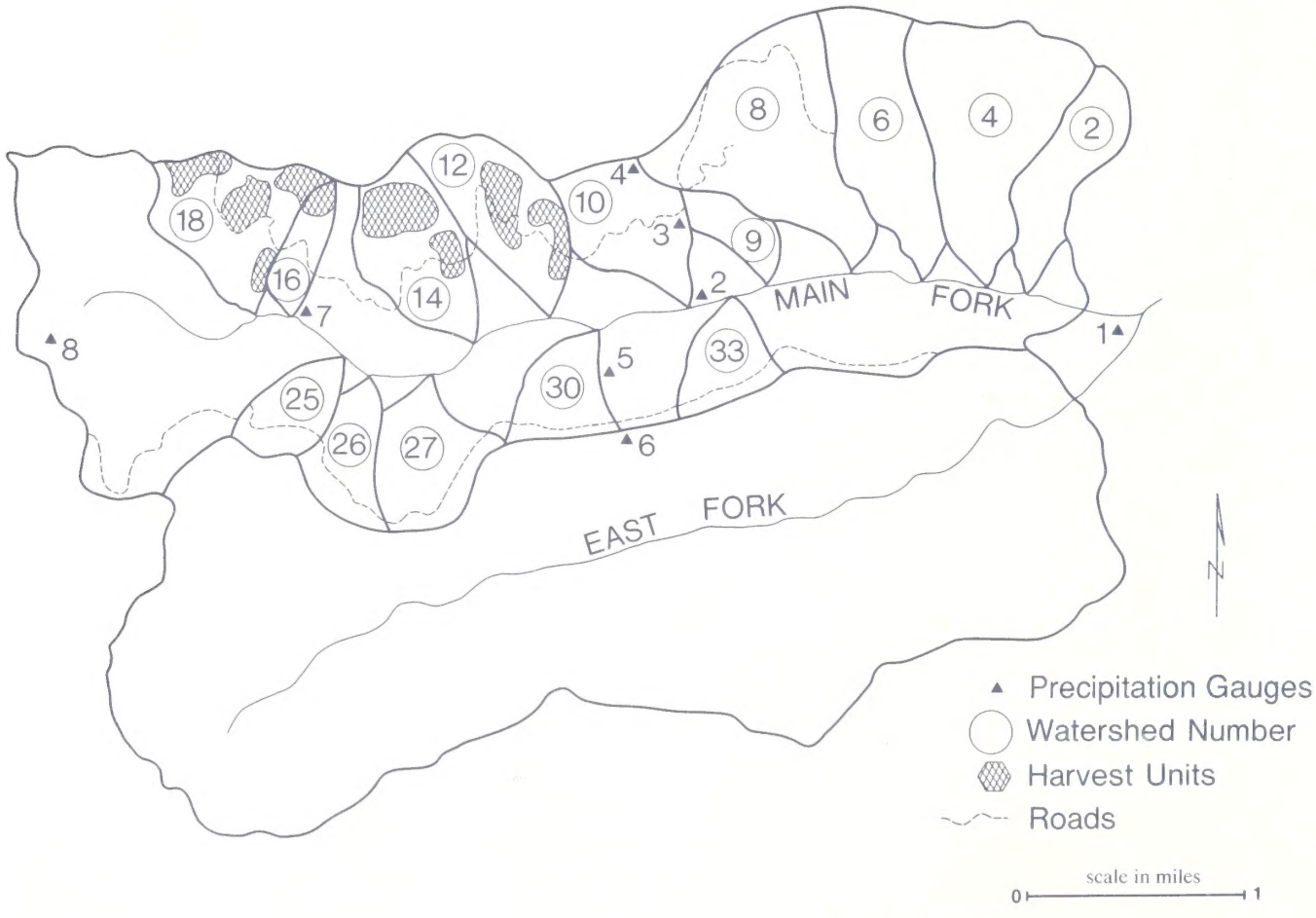

Figure 1—Map of the Horse Creek watersheds nested in the Main Fork drainage showing road, harvest unit, and precipitation gauge locations.

These watersheds are moderately dissected lands in the Selway subsection of the Northern Rocky Mountain Physiographic Province (Arnold 1975). Elevations range from 4,100 to 5,916 ft. Median side slopes are 31 percent, but slopes in excess of 65 percent are common adjacent to the main channel in the lower portions of the Main Fork watershed. The general aspect of the 10 watersheds on the north side of the Main Fork is southerly and for the five watersheds on the south side of the Main Fork, northerly. These small watersheds were completely covered, predominantly with grand fir (*Abies grandis* [Dougl.] Lindl.) and associated species. The most prevalent habitat types in these watersheds are western redcedar/queencup beadlily (*Thuja plicata/Clintonia uniflora*) and grand fir/queencup beadlily (*Abies grandis/Clintonia uniflora*).

The average annual precipitation is about 46 inches, with about 70 percent occurring as snowfall during November through April. The winters are wet and moderately cold. Pacific air masses frequently affect the climate. In the winter months these warm moist air masses produce a heavy wet snow, and winter melt is not uncommon. Continental air masses also may affect the winter climate producing colder air temperatures and a drier snowfall. January is the coldest month with daily temperatures averaging 23 °F. The summers are hot and dry with only a few convective storms in July, August, and September. During the warmest month, July, average daily temperatures are 60 °F.

High streamflows generated by snowmelt or rain and snowmelt usually occur in April, May, and June, although the initial increase in streamflow is usually apparent by the middle of March. About 65 percent of the annual streamflow occurs in April through June. The snow water equivalent on April 1 averages about 58 percent of the total annual precipitation. The melt from the snowpack plus precipitation of about 10 inches in April through June produce spring streamflows that are 20 to 50 times as large as the lowest annual streamflows. The largest average daily streamflow measured on control watershed 6, 6.72 ft^3/s (16.8 $ft^3/s/mi^2$), was the result of 0.7 inch of rain on a melting snowpack in May 1976. Streamflows diminish over the summer months, and the lowest flows occur in September or October. Streamflow usually remains low throughout the fall and winter, gradually increasing in response to fall rains or winter melt. Infrequently a rain-on-snow event in late fall or winter may also generate high streamflows. For example, on the control watershed, watershed 6, over 12 years, only once has a late fall rain-on-snow event produced streamflow that exceeded the maximum streamflow during the following spring snowmelt. This particular storm produced about 3 inches of rain over 2 days. Air temperatures during the storm were in the 32 to 45 °F range.

The parent material in the area is classified as border zone material adjacent to the Idaho batholith. The majority of the parent material is metamorphosed sedimentary material correlated with the Belt Super Group. This metasedimentary material is varied and intergrades from quartz-biotite-plagioclase gneisses and schist to biotite-plagioclase quartzites (Greenwood and Morrison 1973). These rocks consist primarily of micaceous gneissic material with large proportions of quartz, plagioclase, muscovite, and biotite. The soils are moderately deep, well drained, loam to sandy loam with a surface layer of loessial silt. The two most extensive soil types are Andic Dystrochrepts and Typic Vitrandepts. The loessial surface layer has a loam to silt loam texture and extends to depths of 7 to 21 inches. The subsoil, extending to depths of 22 to 28 inches, has a loam to sandy loam texture, and the substratum, extending to depths of 40 to 61 inches, has a sandy loam to very gravelly sandy loam texture.

MANAGEMENT ACTIVITIES

In the summer of 1978, single-lane midslope logging roads were constructed in watersheds 18, 16, and 8 and in the summer of 1979, in watersheds 14, 12, and 10. The road tread is typically crowned or insloped with an inside ditch-relief culvert drainage system. The roads occupy from 3 to 5 percent of the watershed area (table 1). Clearcut harvesting, in patches ranging from 9 to 35 acres, took place in 1981 and cleared 20.9 to 32.6 percent of the area in watersheds 18, 16, 14, and 12. Tractor logging was done in watershed 18, 16, and 14, and skyline logging was used in watershed 12. The units were broadcast burned in the fall of 1981 except for the unit in the northwest portion of watershed 18, which was burned a year later. In 1983 and 1984 a ridgetop road was constructed in watersheds 25, 26, 27, 30, and 33. Table 1 and figure 1, respectively, describe the physical characteristics of these watersheds and the management activities and show the road and harvest unit locations.

METHODS

The streams draining the 10 small watersheds on the north side of the Main Fork were instrumented with H-type flumes and stage recorders and have provided continuous streamflow data since 1975. Those watersheds on the south side of the Main Fork have provided continuous streamflow data from 1979 through 1983. Stream stage was digitized from the stage recorder strip charts at hourly intervals, and mean daily stream discharge was calculated. The streamflow variables discussed in this paper were developed using mean daily stream discharge data, with the exception of the instantaneous peakflow, which represents the maximum instantaneous stream discharge.

In the Main Fork drainage are eight precipitation gauges (fig. 1). Table 2 gives the elevation and site characteristics of each gauge location. Subsets of these gauges were used to develop relationships between gauge elevation and annual precipitation for south and north aspect watersheds in Horse Creek.

The streamflow variables that were evaluated for the effects of vegetation removal by roading and harvesting were the annual stream discharge and several variables indexing high streamflows of different durations. Those variables were the maximum instantaneous stream discharge, the maximum mean daily stream discharge, the stream discharge equaled or exceeded 5 percent of the

Table 1—Selected characteristics of the Horse Creek watersheds

Watershed	Area	Mean elevation[1]	Stream order	Dominant aspect	Road area	Harvest area	Harvest and road area
	Acres	*Feet*		*Degrees*	*Acres*		*Percent*
2	143	4,940	1	200			
4	348	4,965	2	185			
6	256	4,950	2	166			
8	364	4,990	2	144	13.5		4.0
9	58	4,780	1	133			
10	161	4,990	2	144	4.2		3.1
12	207	5,165	2	161	8.4	67.4	36.6
14	154	5,235	2	134	3.4	41.5	29.2
16	54	5,443	1	198	2.2	11.3	25.0
18	213	5,458	2	177	9.2	61.9	33.4
25	79	5,320	2	44	3.0		3.8
26	95	5,255	1	13	3.6		3.8
27	168	5,180	2	9	5.1		3.0
30	92	5,015	2	34	3.7		4.0
33	82	4,902	2	358	3.3		4.0

[1]Average of the maximum and stream gauge elevations.

Table 2—Elevation and length of record for the Horse Creek precipitation gauges[1]

Station number	Elevation	First complete record year	Site characteristics
	Feet		
1	4,130	1966	Mouth of drainage
2	4,460	1977	Valley
3	4,910	1979	Midslope, south aspect
4	5,420	1978	Ridgetop
5	4,840	1979	Midslope, north aspect
6	5,250	1979	Ridgetop
7	5,000	1979	Valley
8	5,600	1966	Head of drainage

[1]Figure 1 shows locations of these precipitation gauges.

year, and the maximum mean monthly stream discharge. Subsequent to the analysis of these streamflow variables, the date at which half the annual streamflow is achieved was also evaluated for possible shifts following road building and harvesting.

Simple linear regressions were developed between the control and treated watersheds for each streamflow variable during the preroad calibration and the postharvest treatment periods. Data from the years when the road was in place, but prior to harvesting, were not used in the analysis. Thus, any changes in the streamflow variables are due to a combination of harvesting and roading.

Analysis of covariance was used to test for significant differences between the slopes and intercepts of the calibration and treatment regressions (Freese 1967), reflecting streamflow responses to the combination of roading and harvesting. The modifications in stream hydrologic factors due to just road building have been previously reported (King and Tennyson 1984).

Estimates of a change in any streamflow variable for the "average" water year were determined by comparing predicted values from the calibration and treatment regressions using the 12-year (1975 through 1986) average of the variable from control watershed 6 as the value of the independent variable. Estimates of the change in the "average" streamflow variables were used in the comparison with the ECA relationships because the ECA procedure is used to estimate average responses and is not driven by specific climatic events.

These watersheds are much smaller than those watersheds on which the ECA procedure is usually applied. However, the relationships in the procedure to estimate annual streamflow under undisturbed conditions and to estimate annual streamflow increases following harvesting and road building are "onsite" responses representing water yields per unit area of ECA disturbance and thus are not a function of watershed size. The increase in the maximum monthly streamflow or other variables describing highflows are related to the area of the watershed. Thus, the responses of the highflow variables from these small watersheds cannot be directly used to improve the relationships in the ECA procedure but will be used to evaluate several assumptions in this procedure.

WATER YIELD VERSUS PRECIPITATION

The ECA procedure estimates average annual water yield from a relationship with average annual precipitation developed by the Soil Conservation Service (Farnes 1972). This relationship was developed using data from about 100 mountain watersheds in Montana ranging in size from 10 to 2,000 mi². Average annual precipitation was extracted from mountain precipitation maps for Montana, developed by the SCS. Average annual runoff was obtained from U.S. Geological Survey streamflow records. In developing this relationship for the Horse Creek watersheds, estimates of annual precipitation were calculated by first developing a linear regression between precipitation gauge elevation and annual precipitation for each water year from 1975 through 1986, using annual precipitation records from seven climatic stations in the Main Fork drainage. Separate elevation versus annual precipitation relationships were developed for the watersheds on the north side of the Main Fork and those on the south side using different subsets of the seven climatic stations. Table 3 shows the linear regressions between annual precipitation and gauge elevation for each water year for the north and south aspect watersheds. In 1975 through 1978 not all of the precipitation gauges were installed, and regressions were developed using data from as few as two gauges. Precipitation gauges 1, 2, 3, 4, and 8 were used to develop the elevation versus annual precipitation relationship for the south aspect watersheds, and gauges 1, 2, 5, 6, and 8 were used for the north aspect watersheds (fig. 1). The annual precipitation for a watershed was then determined as the sum of the area weighted annual precipitation in 200-ft elevation zones. Average annual precipitation was calculated for the 1975 through 1986 period for the watersheds on the north side of the Main Fork and for the 1979 through 1983 period for the watersheds on the south side of the Main Fork. Stage recorders were removed from the five watersheds on the south side of the Main Fork at the end of the 1983 water year.

Figure 2 shows the relationship between average annual precipitation and water yield developed by the Soil Conservation Service. The figure also plots the estimated average annual precipitation versus water yield for the Horse Creek watersheds for the years of 1975 through 1986. Average annual precipitation and water yield for those years prior to management activities were adjusted to reflect averages for the 1975 through 1986 period based on the precipitation averages for control watershed 6. Except for watershed 18, these watersheds produced less runoff for a given amount of annual precipitation than would have been estimated using the SCS curve. In general, as the mean elevation of the watersheds increase, the data plot closer to the SCS curve. For watersheds 2 and 33, the two lowest elevation watersheds, use of the

Table 3—Annual linear regressions between precipitation gauge elevation and annual precipitation for the south and north aspect subwatersheds at the Horse Creek administrative-research site

Model: Annual precipitation (in) = β_0 + β_1 elevation (ft)

Year	$\hat{\beta}_0$	$\hat{\beta}_1$	N	R^2
South aspect regressions:				
1975	2.28	0.0103	2	—
1976	11.55	.0095	2	—
1977	–5.56	.0082	3	0.99
1978	22.72	.0057	4	.87
1979	2.55	.0065	5	.77
1980	23.14	.0044	5	.93
1981	30.11	.0024	5	.77
1982	35.26	.0022	5	.21
1983	20.36	.0034	5	.77
1984	24.87	.0054	5	.90
1985	25.18	.0023	5	.57
1986	20.21	.0042	5	.61
North aspect regressions:				
1979	–4.51	.0080	5	.74
1980	16.43	.0058	5	.66
1981	27.51	.0029	5	.61
1982	27.14	.0042	5	.65
1983	22.25	.0029	5	.42

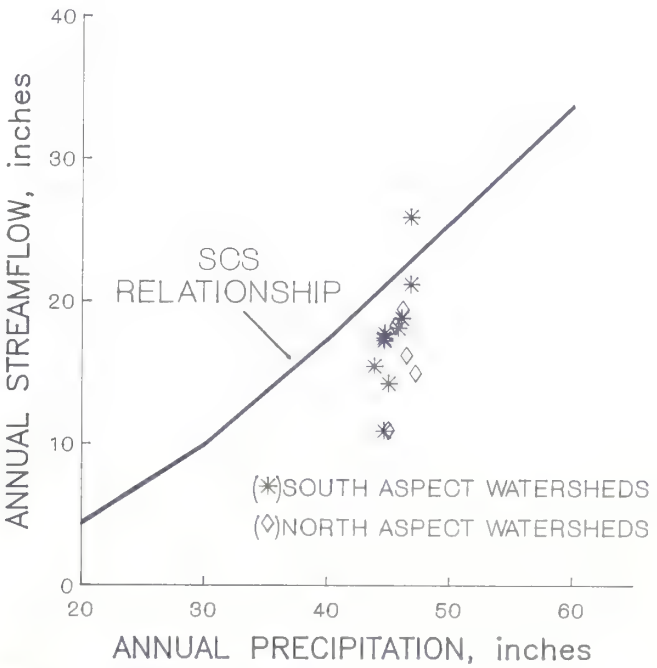

Figure 2—Relationships between average annual precipitation and average annual streamflow for the Horse Creek watersheds compared to a relationship developed by the Soil Conservation Service (Farnes 1972).

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SCS curve would overestimate annual runoff by 9.9 and 10.5 inches respectively. On average the SCS curve overestimated water yield by about 4.5 inches for the Horse Creek watersheds. Because of the narrow range of the adjusted average annual precipitation for these watersheds, 44 to 47 inches, these data are not useful for comparison with the slope of the SCS relationship.

The data used to develop the SCS relationship between annual water yield and annual precipitation were from varied site conditions. Generally, those watersheds with deeper soils and a dense forest cover produce less streamflow for a given annual precipitation than those with thin soils or sparse timber. It is possible that the Horse Creek watersheds produced less yield than most of the watersheds used to develop the SCS relationship because of their relatively deep (4 to 6 ft) soils and dense tree cover.

The annual water yield varied considerably during the calibration period from only 4.45 inches from watershed 2 during the droughty year of 1977, up to 41.95 inches from watershed 18 during the extremely wet year of 1976. For the 12 years of annual streamflow measurements at the control watershed 6, the average and standard deviation are 17.2 and 6.03 inches, respectively. Estimated average annual streamflows for the four harvested watersheds, prior to any management activities, are 18.1, 18.8, 21.2, and 25.9 inches for watersheds 12, 14, 16, and 18, respectively. The portion of annual precipitation appearing as streamflow ranges from an average of 39 percent for watershed 6 up to an average of 50 percent for watershed 18, generally increasing with the mean elevation of the watersheds. Evapotranspiration and interception losses, estimated as the difference between average annual precipitation and streamflow, averaged about 23 inches on watershed 18 and between 27 and 28 inches on watersheds 6, 12, 14, and 16. Thus, there is a large potential to increase streamflow following activities that remove vegetation, reducing evapotranspiration and interception losses and altering snow accumulation and melt.

INCREASE IN ANNUAL WATER YIELD

The four watersheds that had road building and harvesting all had statistically significant increases in annual water yield ($\alpha = 0.01$). Figure 3 shows the annual streamflow relationships between the treated and control watersheds for the calibration and postharvest periods. For all four watersheds the slopes of the preharvesting and postharvesting regressions are similar, indicating a fairly constant volumetric increase in annual streamflow regardless of whether it was a low or high runoff year. For each water year, the increases in annual water yield were highly correlated with the watershed area in equivalent clearcut condition (fig. 4). The slope of the linear

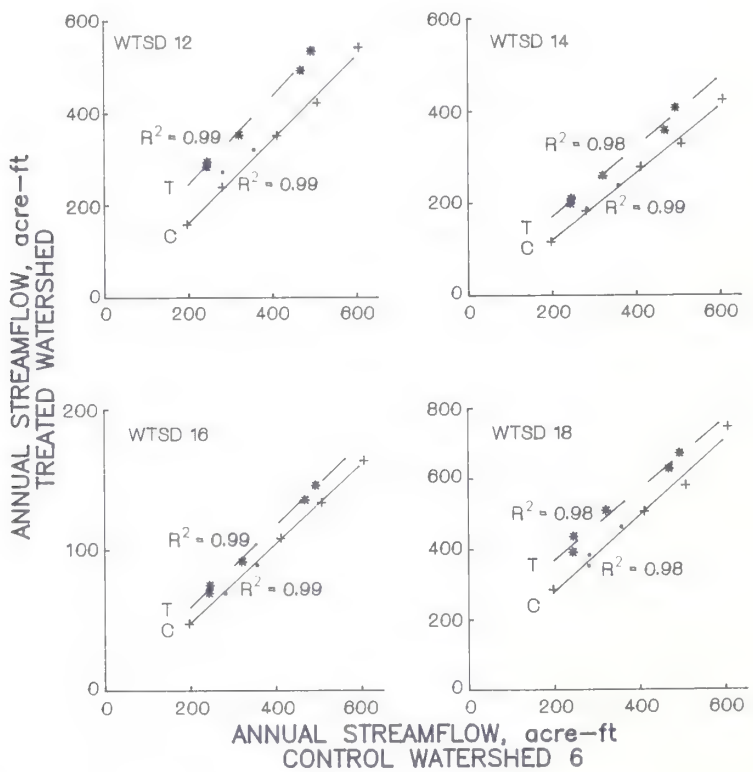

Figure 3—Calibration (C) and treatment (T) linear regressions for annual streamflow for the four Horse Creek watersheds in which road building and harvesting occurred. The data points with a solid dot symbol are for years between road building and harvesting and were not used in either regression.

regressions shown in figure 4 represents the depth increase in feet in annual water yield for the 5 years following clearcut harvesting (no intercept coefficient). Increases in annual water yield from the areas in harvest units and roads averaged 12.0 inches in 1982, 15.9 inches in 1983, 15.7 inches in 1984, 12.2 inches in 1985, and 14.6 inches in 1986. The solid line in figure 4 represents the linear regression through estimates of the average increases in annual water yield. These average increases were estimated using the 12-year average annual water yield from the control watershed as the independent variable, and calculating the difference between the predicted values from the calibration and treatment regressions. The slope of the solid regression line represents an average increase of 14.1 inches on the areas in roads and harvest units. For watersheds 12, 14, and 16 this increase is equal to about half of the 27 to 28 inches previously lost to evapotranspiration and interception. On watershed 18, an average increase in annual water yield of 14.1 inches is equivalent to 61 percent of the previous losses to evapotranspiration and interception. However, the streamflow increases are not only attributed to reductions in evapotranspiration and interception losses but also to modifications in snow accumulation and melt on the open areas. There were no measurements of soil water content or snow accumulation and melt to allow partitioning of the water yield increase by the processes being altered.

Increases in average annual water yield, on the areas with vegetation removed, are predicted in the ECA model as a function of the elevation of the areas in an equivalent clearcut condition (fig. 5). Because this relationship uses a percentage increase, it is important that estimates of the preharvesting average annual runoff be fairly accurate. The predicted increase in average annual yield increases with elevation in response to higher precipitation. At the elevation where tree density begins to decline and up into the alpine zone, the average annual yield increase declines with increasing elevation. For the elevation zone where road construction and timber harvesting occurred in the Horse Creek watersheds, the ECA curve predicts a 37 to 38 percent increase in the average annual water yield on the equivalent clearcut areas. Increases in average annual water yield, determined as the difference between the calibration and treatment regressions at the mean value for the control watershed were 52.0 percent on watershed 18, 51.2 percent on watershed 16, 78.7 percent on watershed 14, and 80.1 percent on watershed 12. These increases are substantially greater than those predicted by the ECA relationship. On average the water yield increase function in the ECA procedure underestimated the actual percentage increase by 44 percent.

An earlier evaluation of the ECA model was conducted on a 950-acre watershed on the Priest River Experimental Forest of northern Idaho (Belt 1980). A 98-acre clearcut and 19.2 acres of logging roads produced an extra 10 inches of annual streamflow over a 5-year postharvest period, compared to the adjacent forested land. Water yield increases on the cleared areas were about 66 percent

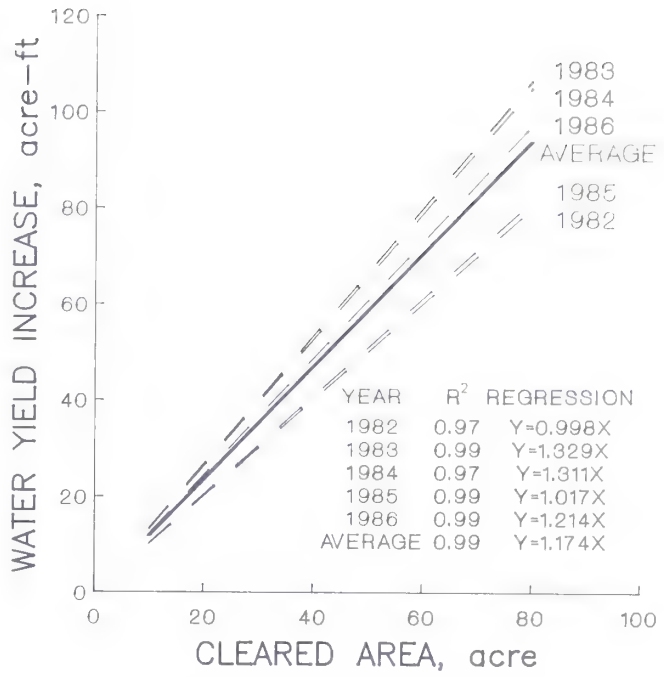

Figure 4—Relationships between the area of the Horse Creek watersheds in roads and harvest units and the increase in annual water yield.

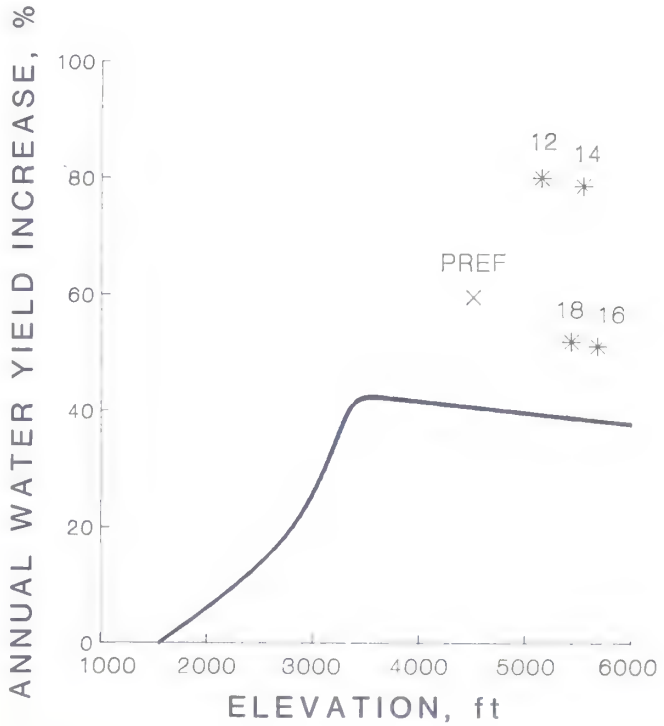

Figure 5—Observed increases in "onsite" annual water yield following road building and harvesting compared with the relationship used in the equivalent clearcut area procedure.

at an average elevation of 4,500 ft (fig. 5, point labeled PREF). In this case, the ECA relationship underestimated the observed increase in onsite annual water yield by 38 percent, which favorably compares with the 44 percent underestimation at the Horse Creek site.

The ECA procedure initially overestimated the average annual water yield from the undisturbed Horse Creek watersheds by about 4.5 inches. The procedure then increases this yield by a percentage that is too low. To some degree these inaccuracies, as compared to the Horse Creek data, compensate. However, inaccuracies in the predictions may also accumulate and lead to estimates of management effects on water yield that are not realistic. Thus, the need for a sound local data base for model calibration.

PEAK STREAMFLOWS

The timber cutting guidelines used with the ECA procedure place a limit on the allowable increase in the highest average monthly yield and in the channel impact period. The reasoning behind this restriction is that the increased energy associated with higher streamflows or the duration of high streamflows has the potential to alter the channel via channel bottom degradation and channel widening. In the ECA procedure the predicted increases in the annual streamflow are partitioned by month over the snowmelt hydrograph as a function of the elevation and aspect of the equivalent clearcut area to determine the increases in the highest average monthly yield. In scheduling harvest entries into a large watershed, harvest units can be spatially arranged on a wide variety of aspect and elevation combinations to minimize increases in the maximum monthly streamflow and stay below previously determined limits.

The modifications in maximum monthly streamflow from the Horse Creek watersheds with harvest units and roads cannot be compared with predicted responses in the ECA procedure because of the small size of the Horse Creek areas. The ECA procedure was developed for much larger watersheds and does not consider modifications in streamflow in headwater basins. However, streamflow responses in Horse Creek during the snowmelt period are useful in examining the appropriateness of two assumptions in the ECA procedure. Because the ECA procedure uses responses in third to fifth order streams, it assumes that limiting streamflow increases in the larger order streams adequately protects the channel system in the lower order streams. This assumption is not stated in any of the ECA literature but is inferred from the method of application in the procedure. The second assumption is that increases in the maximum monthly streamflows represent increases in streamflow sufficient to alter the channel. The responses in several streamflow variables representing different durations of highflows and previously developed relationships between bedload sediment transport and streamflow will be used to evaluate these two assumptions.

In 1975 and 1976 bedload transport rates were measured in selected Horse Creek streams during the snowmelt period and terminating in July. Bedload rating curves were developed regressing the logarithm of the bedload transport rate against the logarithm of stream discharge. Mean daily stream discharge for water years 1975 and 1976, ranked from highest to lowest, and the bedload transport rating curves were used to produce the relationships shown in figure 6 for control watershed 6. These relationships demonstrate that the majority of the annual bedload sediment is produced by relatively few days of high streamflows. The maximum mean daily flow generated about 10 percent of the annual load, and half the annual load is produced by the 7 or 8 highest flow days. Relationships for the other watersheds were similar in that relatively few days of the highest stream discharges transport most of the annual bedload. Thus, it is relatively few high flow days that have the potential for shaping the channel. Increases in short duration high flows following harvesting and road building are more important in terms of potential channel erosion and bedload transport than increases in longer duration high flows such as the maximum mean monthly streamflow or the channel impact period.

Megahan (1979) suggests that bank-full flows are large enough to have a major effect on channel form. Using a return period of 1.5 years for instantaneous bank-full flows (Leopold and others 1964), the bank-full flow for watershed 6 is 3.06 ft^3/s. The mean maximum monthly streamflow for watershed 6 is only 1.67 ft^3/s, much lower than the bank-full flows capable of altering the channel. The 12-year average maximum daily flow and average maximum instantaneous flow for this watershed are 3.68 and 4.10 ft^3/s, respectively. The maximum daily and maximum instantaneous flows for the average year are

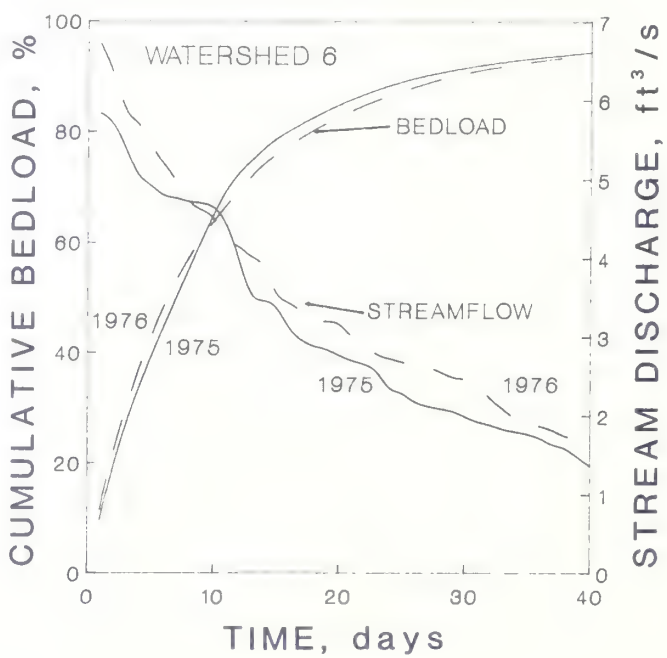

Figure 6—Cumulative bedload sediment production and mean daily stream discharge for the highest streamflow days, in decreasing order, for control watershed 6 during water years 1975 and 1976.

large enough to be shaping the channel. Using this approach to estimate the magnitude of channel-forming flows, only the 4 to 6 days of highest flows in an average year would exceed bank-full flow and have the capability to modify the channel. Even in the year of highest flows, 1976, bank-full flow was exceeded on only 20 days. This approach to defining channel-forming streamflows supports the previously discussed bedload transport approach in that relatively few days of highest streamflow have the potential to shape the channel. Therefore, increases in short-duration highflows are more important than longer duration highflows in shaping the channel, and any procedure to estimate streamflow responses and set limits on harvesting should focus on the expected changes in these shorter duration highflows.

The responses in four streamflow variables representing different durations of high streamflows were evaluated for the Horse Creek watersheds. These variables are the maximum instantaneous streamflow, the maximum daily streamflow, the streamflow equaled or exceeded 5 percent of the year, and the maximum monthly streamflow. Figure 7 illustrates the average response in these four variables following harvesting and road building. The open bars represent the predicted value for the watershed prior to disturbance, and the cross-hatched portion of the bars represent the increase observed after road building and harvesting for the average year. The calibration and treatment period regressions for these variables are included in the figures 8-11. In these figures the data points with a solid dot symbol are for those years between road building and harvesting and were not used in either regression.

The size of the increase in any of the peakflow variables is influenced to a degree by when the extra streamflow is produced from the harvest units and roads compared to the undisturbed portion of the watershed. In these south-aspect watersheds, patch clearcutting was an attempt to promote earlier melt in the harvest units such that increases in streamflow would be prior to the normal peakflows. An analysis of the date at which half the annual streamflow was produced indicated that only in watershed 12 were streamflow contributions significantly advanced in the water year. The half-flow date was advanced by about 8 days ($\alpha = 0.05$). The clearcuts in watershed 12 were free of snow about 2 weeks earlier than the clearcuts in the other watersheds. An algorithm developed by Swift (1976) was used to calculate the potential solar radiation received by the individual harvest units. The steeper, more southerly facing units in watershed 12 receive the highest potential solar radiation from October through March. The harvest units in watershed 12 are at lower elevations than the units in the other watersheds, both in terms of actual elevation and relative elevation within the watershed. Average ambient air temperatures are probably slightly higher in the harvest units in watershed 12 because of their lower elevation, which also may promote earlier melt.

The maximum instantaneous and maximum daily flows are usually the result of rain on an already melting snowpack for the Horse Creek watersheds. Increases in these

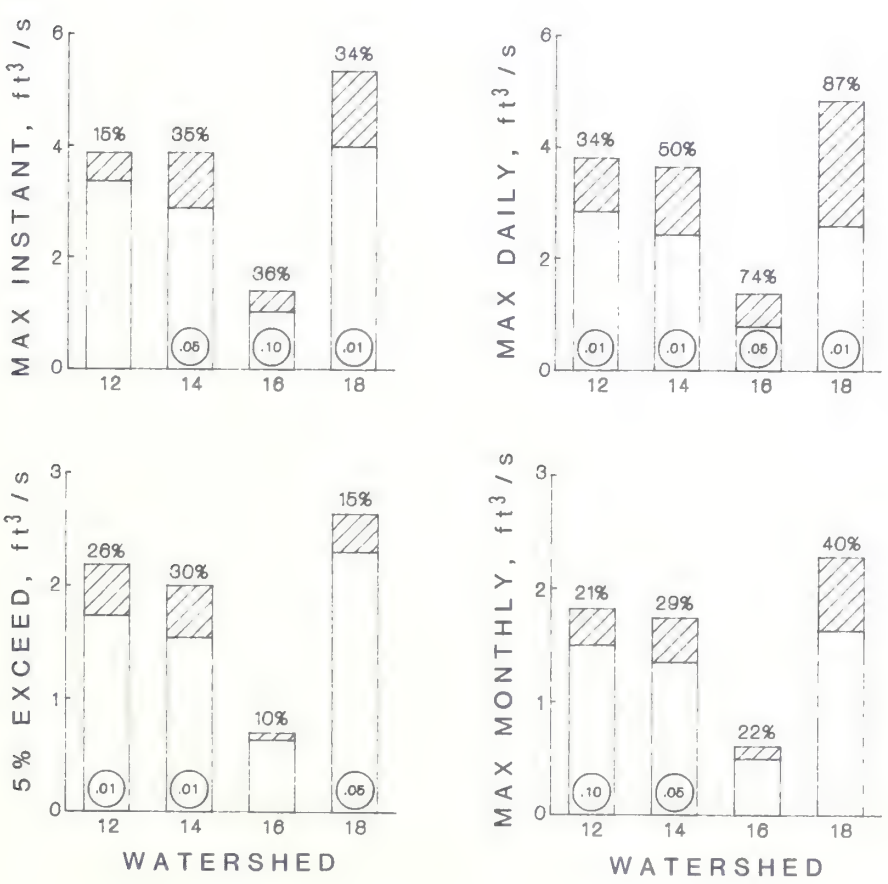

Figure 7—Average responses to road building and harvesting in variables indexing high streamflows for the four Horse Creek watersheds. The percentage above each bar is the average percent increase in that variable and the circled value is the alpha level of significance.

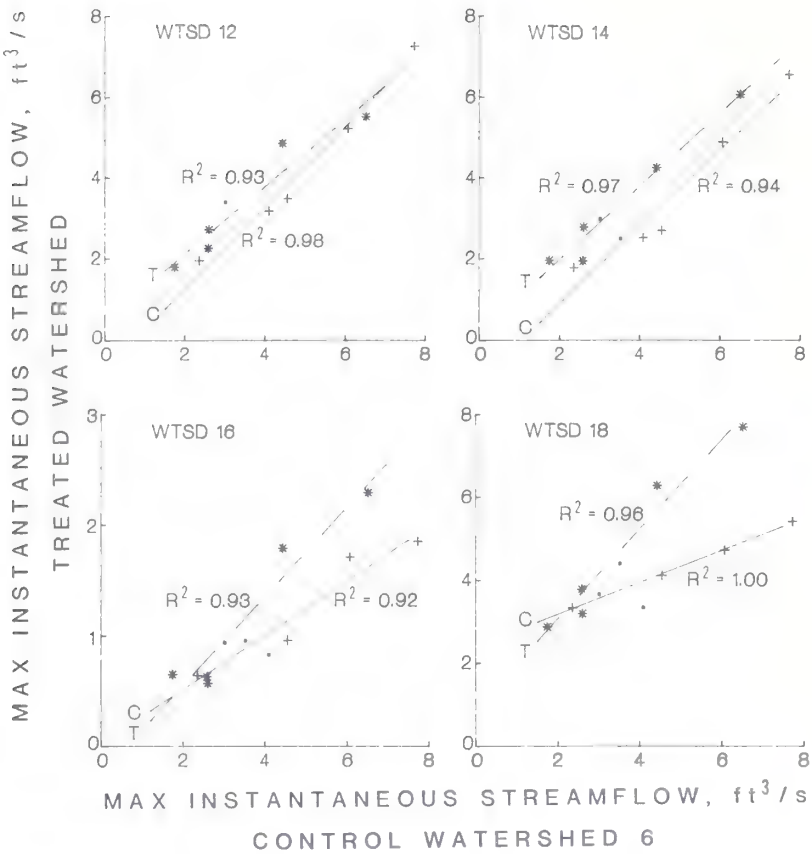

Figure 8—Calibration (C) and treatment (T) period regressions for maximum instantaneous streamflow for the four Horse Creek watersheds in which road building and harvesting occurred.

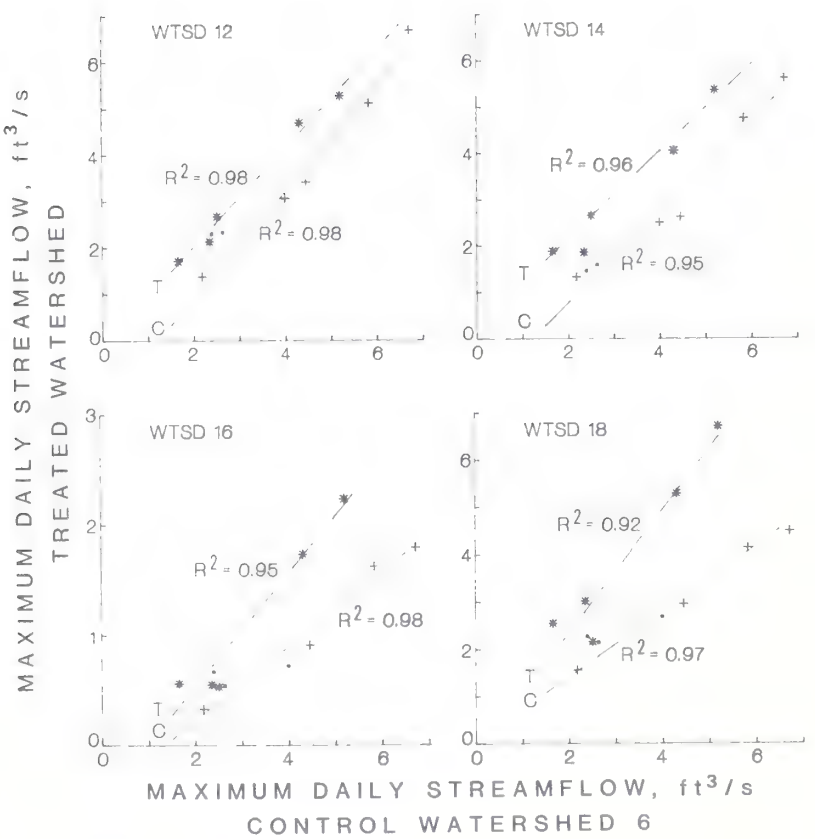

Figure 9—Calibration (C) and treatment (T) period regressions for maximum daily streamflow for the four Horse Creek watersheds in which road building and harvesting occurred.

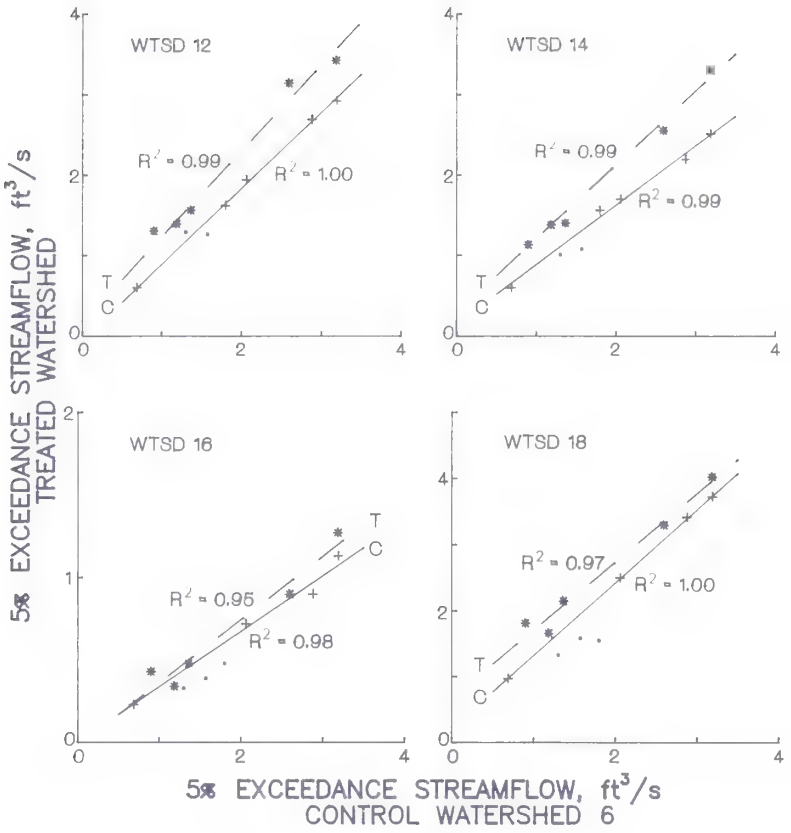

Figure 10—Calibration (C) and treatment (T) period regressions for streamflow equaled or exceeded 5 percent of the year for the four Horse Creek watersheds in which road building and harvesting occurred.

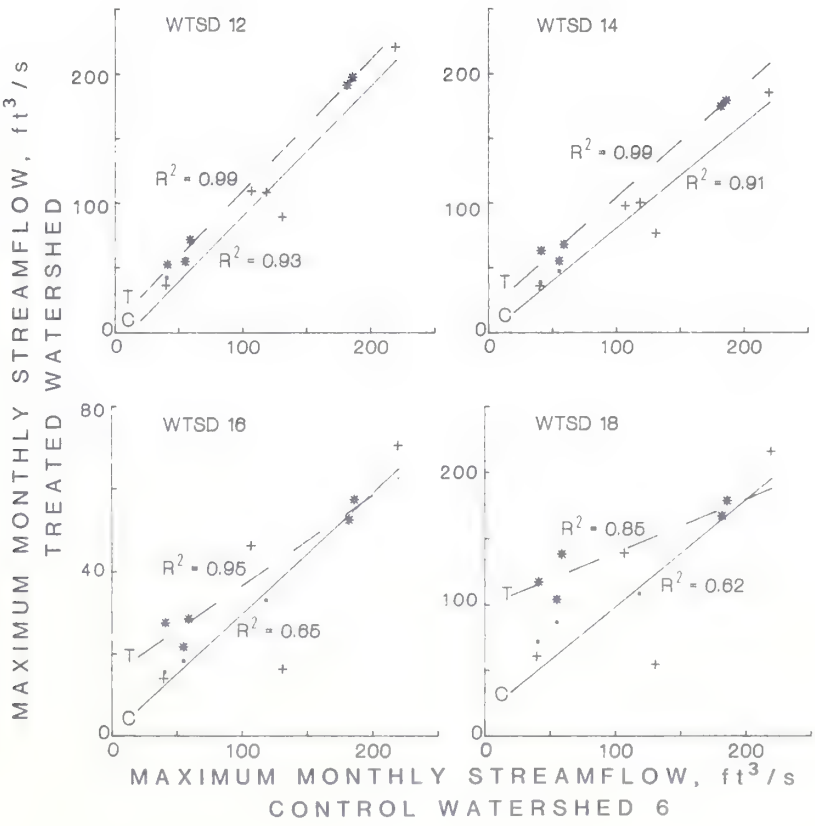

Figure 11—Calibration (C) and treatment (T) period regressions for maximum monthly streamflow (May) for the four Horse Creek watersheds in which road building and harvesting occurred.

two variables were directly proportional to the cleared area on those watersheds where streamflow contributions were not advanced earlier in the year, watersheds 14, 16, and 18 (fig. 12). In these watersheds, increases in the maximum instantaneous and maximum daily stream discharge of 1 ft^3/s would require about 49 and 31 acres in cleared condition, respectively. The largest increases were in watershed 18 with 71 of its 213 acres in openings. In watershed 18 average maximum instantaneous flows increased by about 1.35 ft^3/s and average maximum daily flows increased by about 2.25 ft^3/s. In watershed 12 increases in these streamflow variables were smaller due to less snow present in the open area at the time of maximum flows. Increases in the instantaneous peak streamflows were not significant ($\alpha = 0.10$) for watershed 12.

Increases in the 5 percent exceedance streamflows were significant ($\alpha = 0.05$) on three of the four watersheds and ranged from 15 to 30 percent. On watershed 16, with only 25.0 percent of its area in equivalent clearcut condition, a significant ($\alpha = 0.10$) increase was not detected. Yet watershed 16 did have large increases in the instantaneous and maximum daily streamflows. Increases in the 5 percent exceedance streamflows were not proportional to the portion of the watershed in equivalent clearcut condition. The increases in the maximum monthly flow (May) were only significant ($\alpha = 0.10$) on watersheds 12 and 14 with 21 and 29 percent increases, respectively. Poor calibration equations (fig. 11) for watersheds 16 and 18 inhibited statistical detection of increases in this variable.

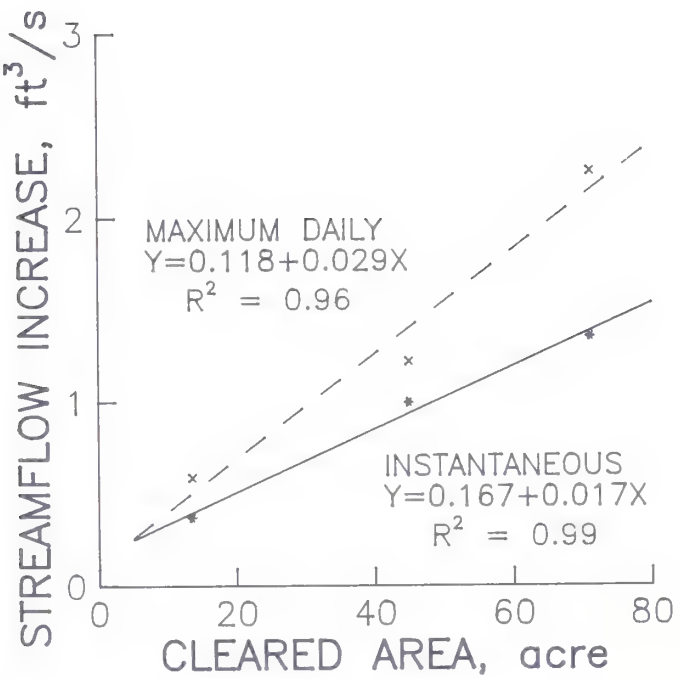

Figure 12—Relationships between area in roads and harvest units and average increases in maximum instantaneous and maximum daily streamflow.

SUMMARY AND RECOMMENDATIONS

Reliable local precipitation and streamflow data are required to develop accurate relationships between average annual precipitation and streamflow. The relationship developed in Montana by the Soil Conservation Service overestimated average annual streamflow for the Horse Creek watersheds by about 4.5 inches. If local data are not available, more accurate predictions may be achieved by using the relationship developed from the Horse Creek site. However, application of this relationship should be restricted to completely forested watersheds in the 4,000- to 6,000-ft elevation zone, with moderately deep well-drained soils in northern Idaho.

The increase in average annual streamflow following harvesting and road building was much larger than predicted in the ECA procedure. The original ECA document (USDA FS 1974, sec. 2, p. 28) suggests that increases of 6 to 13 inches in average annual water yield might result from harvesting in the 4,000- to 6,000-ft elevation zone in the Nez Perce National Forest in Idaho. Average increases were 14 inches in this same elevation zone in the Horse Creek watersheds. Based on results from the Horse Creek administrative-research site and the Priest River Experimental Forest, it is recommended that a 69 percent increase factor be used for moderately deep soils in the 5,000- to 6,000-ft elevation zone in northern Idaho.

High streamflows capable of altering the channel are of short duration in the average water year. For these small Horse Creek watersheds the largest 7 or 8 days of streamflow account for the majority of the bedload movement, with the single highest daily flow accounting for about 10 percent of the annual bedload production. Average monthly streamflows are usually not a good index of bedload transport, and "changes in average annual monthly peakflows have no meaningful effect on sediment transport" (Megahan 1979) and are thus poor indicators of changes in channel-forming flows. This would also hold true for the 5 percent exceedance flows in the average water year.

On south-facing first and second order drainages, advancing snowmelt through patch clearcutting was not readily achieved. Harvest units placed on those slope, aspect, and elevation combinations to maximize winter and spring solar radiation to the snowpack have the most likelihood of advancing melt. If melt is not advanced, increases can be expected in the instantaneous peak and maximum daily streamflows on the order of 0.2 and 0.3 ft^3/s, respectively, for every 10 acres in cleared condition. While it is not appropriate to suggest some absolute limit to harvesting in low-order watersheds, the results would indicate that harvesting in low-order watersheds that have channel conditions that may be sensitive to increases in short duration peakflows should proceed on a conservative basis. In many instances the channels may be stable enough to withstand fairly large increases in short duration peakflows without any channel alteration. Additional research is needed to understand how channels respond to both increased flows and sediment loads and how to identify channels that might be the most sensitive to change. There are other effects of increases in

short-duration peakflows that should also be considered. Because sediment transport rate is usually exponentially related to streamflow, increases in peakflows could create a situation where accelerated sediment from roads or harvest units is more efficiently transported downstream. In certain situations, the increases in peakflows from small watersheds may be additive in the higher order stream channels (Harr 1986).

Current procedures for estimating the hydrologic responses to timber removal of third to fifth order streams often ignore what may be hydrologically important modifications in the low-order streams. Hydrologists should consider the potential modifications to headwater basins in scheduling harvest entries and locating harvest units, especially when conditions are such that the stream system is likely to be sensitive to streamflow modification.

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Increases in annual streamflow and peak streamflows were determined on four small watersheds following timber harvesting and road building. The measured hydrologic changes are compared to those predicted by a methodology commonly used in the Forest Service's Northern Region, the equivalent clearcut area procedure. Increases in peak streamflows are discussed with respect to their potential to modify the channel system.

KEYWORDS: timber harvest, water yield

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Native Species Establishment on an Oil Drill Pad Site in the Uintah Mountains, Utah: Effects of Introduced Grass Density and Fertilizer

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RESEARCH SUMMARY

The effects of introduced grass seeding density and fertilizer on native species establishment were examined on an oil drill pad site in the Uintah Mountains, UT. Seeding density treatments consisted of seeding native species at a rate of 215/m^2 with three levels of introduced grasses: (1) none, (2) 215/m^2, and (3) 545/m^2. The fertilization treatments were nonfertilization and a one-time fertilization that consisted of 56 kg/ha of N applied as NH_4NO_3, 56 kg/ha of P applied as P_2O_5, and 28 kg/ha of K applied as K_2O. Increasing introduced grass seeding density resulted in significantly higher introduced grass biomass ($p < 0.05$), but native biomass showed no response and colonizer biomass decreased ($p < 0.05$). Of the seeded introduced grasses, smooth brome, intermediate wheatgrass, and orchardgrass had consistently higher biomass than meadow foxtail and Timothy. The native species, slender wheatgrass, muttongrass, tufted hairgrass, and western yarrow had high establishment, while spike trisetum, everlasting, silky phacelia, serviceberry, mountain big sagebrush, and Woods rose exhibited poor establishment. Two years after fertilization there were no significant differences in soil NO_3–N or exchangeable K between fertilized and unfertilized treatments, but significantly higher available soil P in fertilized treatments ($p < 0.01$). Fertilization resulted in significantly higher biomass of introduced grasses, natives, and colonizers in year 1 ($p < 0.001$), but by year 3 there were no significant differences between fertilized and unfertilized treatments for any of the species. Native species biomass exibited less extreme responses to the one-time fertilizer application than introduced grasses and showed relatively larger yearly increases in unfertilized treatments. During the 3-year study colonizer biomass exhibited large yearly declines regardless of fertilizer treatment ($p < 0.01$). Methods used in the revegetation of similar sites should be determined by the inherent regenerative capacity of the site and the desired end land use.

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Jeanne C. Chambers

INTRODUCTION

Native species are widely used in mined land reclamation to meet legal requirements. The Surface Mining Control and Reclamation Act (SMCRA) of 1977 requires the use of native species for coal mine revegetation unless introduced species are specifically approved by the regulatory authority. Individual State regulations for coal mining operations must equal or exceed those of SMCRA. Noncoal mining is governed solely by the States, and large differences exist in the regulations. In Utah the regulations for noncoal mines or other disturbances have no requirements for native species.

Ecologically, native species have many desirable attributes for disturbed land reclamation. In extreme environments such as harsh climates and toxic spoils, natives may be the only species capable of surviving and reproducing. Including native species in seeding mixtures can enhance species diversity and may accelerate successional processes. Diversity has been correlated with long-term stability and productivity (Root 1973; Tahvanainen and Root 1972), and ecosystems with several types of species are more likely to persist following natural disturbances such as grazing and fire (Harper 1977; McNaughton 1977; Mellinger and McNaughton 1975). In addition, vegetation diversity is frequently correlated with the diversity of animal species (Southwood and others 1979).

Knowledge of the establishment characteristics of native species is essential for the successful reclamation of disturbed land with these species. When native species are included in a seeding mixture, they are often sown with rapidly growing introduced species. Studies that have examined the interactions between natives and introduced species indicate that seeding density, species composition of the seeding mixture, and rate and frequency of fertilization affect native species establishment and ultimate stand composition (Brown and others 1984; DePuit and Coenenberg 1979).

Introduced and cultivated species frequently have higher growth rates, lower root to plant ratios, and higher nutrient uptake efficiency than native species (Chapin 1980). Given the proper growing conditions, these species exhibit highly positive growth responses to N and P fertilization (Aldon and others 1976; DePuit and others 1978; Hanson and others 1976; Hodder and others 1972; Houston and Hyder 1975). At high rates of fertilization species that exhibit the greatest growth response, frequently annuals and introduced grasses, tend to outcompete slower growing natives (Berg 1980; DePuit and Coenenberg 1979). In addition, N-fixing legumes often show a negative response to high levels of N fertilization when growing in mixtures with grasses (DePuit and Coenenberg 1979). The frequency of fertilization also affects individual species' responses and, ultimately, stand composition (Brown and others 1984). Repeated fertilizer application can stimulate introduced species production over long periods. Native species development in stands that include introduced species is often greatest under no and first-year fertilization.

This study addressed the question: What effects do seeding density of introduced grasses and fertilization have on establishment and growth of native grasses, forbs, and shrubs? I tested three null hypotheses: (1) increasing density of introduced grasses would not lower establishment and growth of native grasses, forbs, and shrubs; (2) fertilization would not have a larger positive effect on the establishment and growth of introduced grasses than on the establishment and growth of native species; and (3) fertilization would not compound the negative effects of increasing introduced grass density on the establishment and growth of native species. I then related the findings of this study to possible reclamation strategies for this and similar sites.

METHODS

The study site is in the northeastern corner of Utah on the north slope of the Uintah Mountains (S24, T3N, R14E) at approximately 2,743 m. The site is in a small basin, 1.2 to 1.6 ha, that was used as an oil drilling pad site by Phillips Oil Company. The company recontoured the basin leaving two sloping faces on the southern end, a large mound on the east, and a small pond on the north. The study plots are in the center of the basin on homogeneous (5 percent slope) terrain.

The soil on the site is a well-drained sandy loam derived from quartzite and sandstone. Average annual precipitation is about 64 cm with April and May the wettest months and precipitation fairly evenly distributed

among the other 10 months (Bengeyfield and others 1980). The vegetation surrounding the area is dominated by lodgepole pine (*Pinus contorta*) with a sparse understory of species such as Oregon-grape (*Berberis repens*) and mountain lover (*Pachystima myrsinites*). Small patches of aspen (*Populus tremuloides*) are interspersed throughout the lodgepole pine, and broad meadows with species such as tufted hairgrass (*Deschampsia cespitosa*) and muttongrass (*Poa fendleriana*) follow the major drainages.

Study Design

The study included three seeding density treatments and two fertilizer treatments in a randomized block design with three replications of each treatment. Each replication was 6.1 by 30.5 m. The density treatments consist of a constant density of natives (215/m^2) seeded with (1) no introduced grasses, (2) an equivalent density of introduced grasses (215/m^2), and (3) three times the density of introduced grasses (645/m^2) (table 1). Seeding densities were based upon pure live seed (PLS) and determined from recommended levels of seeding densities for mined land revegetation in general and for seeding mixtures of natives specifically (USDA FS 1979).

The fertilization treatments I chose were nonfertilization and an "optimal" level. I based the "optimal" level on the recommendations of Tiedemann and Lopez (1982) and took into account the initial levels of N, P, and K in the soil. The levels and forms of nutrients were 56 kg/ha of N applied as NH_4NO_3, 56 kg/ha of P applied as P_2O_5, and 28 kg/ha of K applied as K_2O.

Seeding Mixture

Table 1 contains a complete list of the species used in this study. The introduced grasses were chosen on the basis of their ability to perform well under climatic and edaphic conditions similar to those that exist on the study site (Thornburg 1982). I selected native species that were colonizers on similar disturbed sites in the area.

Seeds of introduced grasses, native shrubs, and western yarrow were purchased. Seeds of the other native species were collected adjacent to the study site during the fourth week of August, allowed to dry for 1 week, and then threshed. Seed weight and number per gram were determined by weighing three replications of 100 seeds of each species. Seed viability of the collected native species was determined from a standard tetrazolium test (Moore 1972). Collected native seeds were about 99 percent pure.

Table 1—Numbers of pure live seeds for native and introduced species used in each treatment

Species	Natives only	Natives and low density introduced	Natives and high density introduced
		Pure live seed/m^2	
Introduced grasses			
Intermediate wheatgrass (*Agropyron intermedium*)	0	43	129
Meadow foxtail (*Alopecurus pratensis*)	0	43	129
Smooth brome (*Bromus inermis*)	0	43	129
Orchardgrass (*Dactylis glomerata*)	0	43	129
Timothy (*Phleum pratense*)	0	43	129
Subtotal	0	215	645
Native species			
Grasses			
Slender wheatgrass (*Agropyron trachycaulum*)	21.5	21.5	21.5
Tufted hairgrass (*Deschampsia cespitosa*)	21.5	21.5	21.5
Muttongrass (*Poa fendleriana*)	21.5	21.5	21.5
Spike trisetum (*Trisetum spicatum*)	21.5	21.5	21.5
Forbs			
Western yarrow (*Achillea millefolium*)	21.5	21.5	21.5
Everlasting (*Antennaria* spp.)	21.5	21.5	21.5
Silky phacelia (*Phacelia sericea*)	21.5	21.5	21.5
Shrubs			
Saskatoon serviceberry (*Amelanchier alnifolia*)	21.5	21.5	21.5
Mountain big sagebrush (*Artemisia tridentata vaseyana*)	21.5	21.5	21.5
Woods rose (*Rosa woodsii*)	21.5	21.5	21.5
Subtotal	215	215	215
Total	215	430	860

The purity, viability, and germinability of purchased seed were determined by the Utah State Seed Lab using the Association of Official Seed Analysts rules for testing seeds (1981). Seeding rates were calculated using purity and germinability for purchased seeds and purity and viability for collected seeds. An additional 20 percent was factored into seeding rates for collected seeds to account for variable germinability.

Field Application

Study plots were installed the last week of September 1984. Site preparation prior to planting included ripping to a depth of 75 cm, removing large rocks, and harrowing. Before planting, seeds were mixed with rice hulls to a total volume of 10 liters. Mixtures were then sown by hand on an individual replication basis. Fertilizer was also applied by hand. A Brillion seeder-packer was used to pack the seed into the seedbed. The study area was fenced to prevent cattle grazing.

Data Collection and Analysis

In the summer of 1985, 10 rectangular quadrats 0.25 m^2 were permanently located within each replication of each treatment using a stratified random method (Chambers and Brown 1983; Knight 1978). Vegetation attributes measured included density, peak standing crop biomass, and cover. Density, defined as the number of plants of each species rooted in a quadrat, was assessed to evaluate the relationship between seeding rate and initial establishment. Because of the problems associated with identifying individual plants, density data were collected only during the first growing season (1985) when it was relatively easy to identify individuals.

I assessed standing crop biomass for each species after peak production in 1985, 1986, and 1987 using a weight-unit estimation method (Carpenter and others 1984). Weight-unit estimation was performed inside each of the 10 permanent quadrats within a replication; in addition, a verification quadrat was clipped within each replication but outside of the permanent quadrats. Samples were dried at 60 °C for 24 h. Standing crop data were collected for seeded species and for colonizer species that were not seeded.

Prior to sampling density and standing crop biomass, I determined cover from 35-mm slides taken of each permanent quadrat. These slides were projected onto a 100-square grid and estimates were made of the areas occupied by five cover classes: aerial vegetation cover, litter, bare-ground, gravel (2 mm to 7.6 cm), and rock (>7.6 cm) (Chambers and Brown 1983).

In 1986 soils were assessed for the edaphic effects of the fertilizer treatments. Two soil cores, 7.5 cm in diameter by 10 cm deep, were collected for each replication of each treatment ($n = 6$). The soils were analyzed by A and L Labs of Omaha, NE, for concentrations of N, P, and K. A specific ion electrode in a saturated calcium sulfate extraction was used to determine NO_3–N (Carson 1980a). Available-P was measured with the Bray-1 procedure using the Fiske-subbarrow reducing agent (Knudson 1980). Exchangeable-K was analyzed in a one normal solution of ammonium acetate adjusted to pH 7.0 (Carson 1980b).

I determined differences in density, standing crop, cover, and soil properties among treatments from standard analysis of variance (ANOVA) techniques. The density and standing crop analyses were based on a comparison of mean values for three species categories: introduced grasses, natives, and colonizers. Because time was a factor in the analysis of standing crop and cover, I used a repeated measures design and conservative degrees of freedom. Mean comparisons were performed using Fisher's Protected LSDs ($p < 0.05$) under the guidelines of Petersen (1977).

RESULTS

Preexisting site conditions had a significant impact on the results of this study. Because the study plots were in a basin, they experienced a perched water table early in the growing season as evidenced by ponded water on the surface and soil mottles. This may have had a negative effect on the seedling establishment and standing crop of all seeded species. The same introduced grasses as were seeded in the current study existed on the research plots prior to study installation from a previous revegetation effort. Although they had been sprayed with glyphosphate the previous summer, they were not completely eliminated. The existence of these grass species may have confounded the results of the seeding density treatments.

To determine the relative importance of the residual introduced grasses, I compared native species and introduced grass densities in the three seeding density treatments in year 1. Native species density varied little among treatments and averaged 8.54 plants/m^2 for the three seeding densities. Introduced grass density was 8.04, 19.40, and 21.12 plants/m^2 in the natives only, low grass density, and high grass density treatments, respectively. Thus, total density of introduced grasses relative to total density of native species in the native's only treatment was similar to that intended for the low grass density treatment. In the other two seeding treatments introduced grass density relative to native species density was intermediate between the intended low and high seeding treatments.

Density

Neither seeding density of introduced grasses nor fertilization had any significant effects on the combined seedling density of introduced grasses, native species, and colonizers during the first growing season (fig. 1). High densities of colonizers relative to those of native species and introduced grasses in the majority of treatment combinations in year 1 appeared to have an overwhelming effect on the analysis. The colonizers had significantly higher densities than either the introduced grasses or native species ($p < 0.05$). Deleting the colonizer species from the overall analysis resulted in significant differences among the three seeding densities and between the

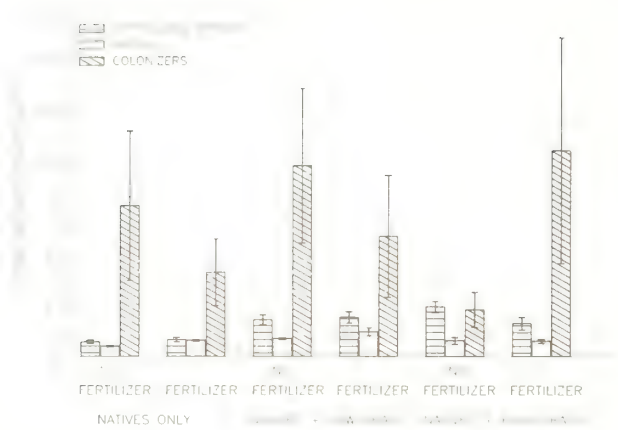

Figure 1—Total density of introduced grasses, natives, and colonizers for 1985 in research plots that were seeded with natives and a zero, low, or high level of introduced grasses and then either fertilized or not fertilized. Values are mean ± S.E., *n* is variable.

introduced grasses and native species (both $p < 0.001$). But there were still no statistical differences attributable to fertilizer. The two seeding treatments that included introduced grasses had higher combined densities of introduced grasses and natives than the natives-only treatment ($p < 0.05$). Because of the residual introduced grasses on the study area, there were no differences between native species and introduced grass densities in the natives-only treatment. However, introduced grass densities were higher than those of native species in the high and low grass density treatments ($p < 0.05$), but not different between the latter two treatments ($p < 0.05$).

Standing Crop Biomass and Individual Species Responses

Figure 2 and table 2 detail the highly significant differences in standing crop biomass among species categories ($p < 0.01$), between fertilizer treatments ($p < 0.001$), and among years ($p < 0.001$). Few significant effects were attributable to grass seeding density. In contrast to the density results, introduced grass standing crop biomass increased with each increase in grass seeding density ($p < 0.05$). Native species showed no differences in standing crop among the three seeding densities and colonizer standing crop decreased with each increase in seeding density ($p < 0.05$).

Total standing crop biomass decreased significantly over time ($p < 0.001$) primarily due to a decline in colonizer species productivity from year 1 through year 3. The effects of fertilizer were not consistent among species categories or over time. Introduced grasses, native species and colonizers had significantly higher standing crop in fertilized than in unfertilized treatments in year 1 ($p < 0.05$). However, by year 3 there were no differences between fertilized and unfertilized treatments for any of the species categories ($p < 0.05$). For introduced grasses

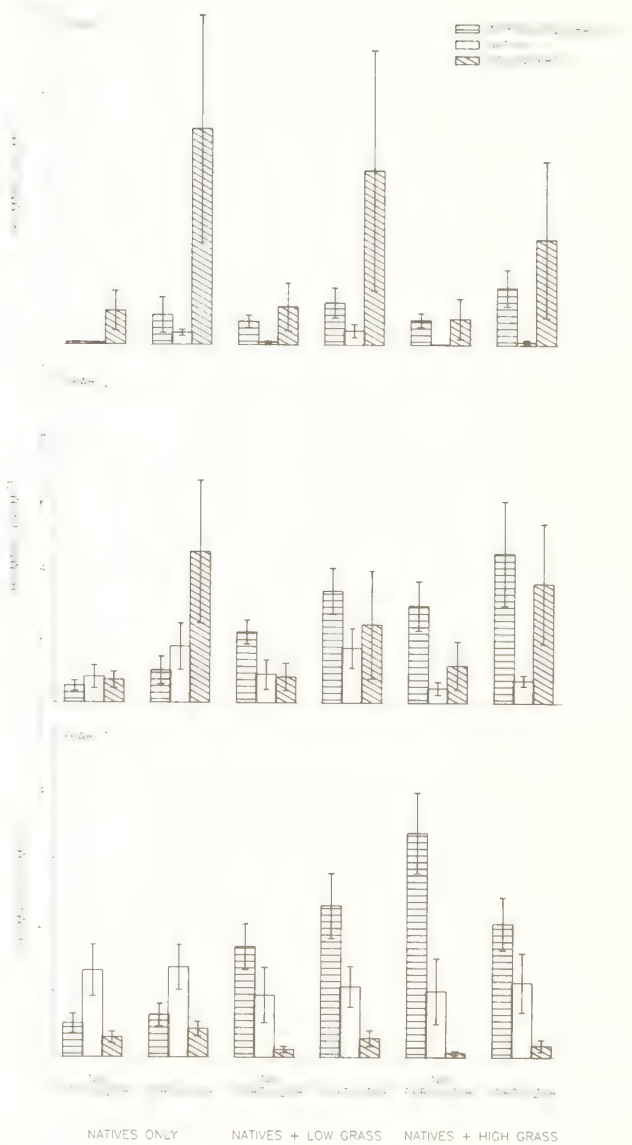

Figure 2—Dry weight biomass of introduced grasses, natives, and colonizers for 1985, 1986, and 1987 in research plots that were seeded with natives and a zero, low, or high level of introduced grasses and then either fertilized or not fertilized. Values are mean ± S.E., *n* is variable.

standing crop decreased between years 1 and 3 in fertilized treatments, but increased in unfertilized treatments ($p < 0.05$). Standing crop of native species did not change over time in fertilized treatments, but increased between years 1 and 3 in unfertilized treatments ($p < 0.05$). Colonizer standing crop decreased significantly over time in both fertilized and unfertilized treatments.

Table 2 shows that first and third year standing crop biomass of intermediate wheatgrass, smooth brome, and orchardgrass were higher than those of meadow foxtail and Timothy. This may be attributable to differences in the initial densities of residual individuals of these species. By year 3 standing crop biomass of slender wheatgrass greatly exceeded that of the other native

Table 2—Standing crop biomass (g/m² dry weight) of species occurring in unfertilized and fertilized plots in years 1 and 3

Species	Year 1		Year 3	
	No fertilizer	Fertilizer	No fertilizer	Fertilizer
Introduced grasses				
Intermediate wheatgrass (*Agropyron intermedium*)	[1]1.68 ± 0.327 (3)[2]	3.97 ± 0.475 (6)	2.18 ± 0.134 (7)	2.81 ± 0.196 (7)
Meadow foxtail (*Alopecurus pratensis*)	.06 ± .002 (5)	.07 ± .007 (4)	1.33 ± .117 (6)	1.10 ± .078 (6)
Smooth brome (*Bromus inermis*)	1.19 ± .058 (7)	2.53 ± .100 (6)	3.18 ± .179 (8)	1.80 ± .051 (7)
Orchardgrass (*Dactylis glomerata*)	.92 ± .080 (8)	3.22 ± .182 (8)	2.65 ± .249 (9)	2.42 ± .202 (9)
Timothy (*Phleum pratense*)	.16 ± .010 (4)	.70 ± .036 (5)	.78 ± .052 (8)	1.06 ± .050 (8)
Native species				
Grasses				
Slender wheatgrass (*Agropyron trachycaulum*)	—	—	2.00 ± .170 (8)	1.99 ± .109 (9)
Tufted wheatgrass (*Deschampsia cespitosa*)	.04 ± .004 (5)	.11 ± .009 (2)	.70 ± .070 (8)	.62 ± .049 (6)
Muttongrass (*Poa fendleriana*)	.18 ± .011 (4)	.55 ± .060 (4)	.22 ± .021 (3)	.45 ± .043 (7)
Spike trisetum (*Trisetum spicatum*)	—	—	—	—
Forbs				
Western yarrow (*Achillea millefolium*)	.14 ± .009 (9)	.92 ± .077 (9)	2.65 ± .023 (7)	.21 ± .009 (6)
Antennaria (*Antennaria* spp.)	—	—	.07 ± .002 (2)	.24 ± .000 (1)
Silky phacelia (*Phacelia sericea*)	.01 ± .000 (1)	15 ± .000 (1)	.14 ± .004 (4)	—
Shrubs				
Saskatoon serviceberry (*Amelanchier alnifolia*)	.20 ± .000 (1)	—	.24 ± .000 (1)	—
Mountain big sagebrush (*Artemisia tridentata vaseyana*)				
Woods rose (*Rosa woodsii*)	.03 ± .005 (2)	.03 ± .005 (2)	.32 ± .026 (4)	.06 ± .000 (1)
Colonizer species				
Winter bentgrass (*Agrostis scabra*)	—	—	.27 ± .021 (3)	.51 ± .111 (3)
Idaho fescue (*Festuca idahoensis*)	.01 ± .00 (1)	—	—	—
Poa (*Poa* spp.)	—	.21 ± .000 (1)	—	—
Alkali sandspurry (*Spergularia diandra*)	5.61 ± .427 (9)	30.23 ± 2.103 (9)	.40 ± .041 (7)	.46 ± .026 (9)
Spreading groundsmoke (*Gayophytum diffusum*)	.21 ± .020 (9)	.20 ± .017 (7)	.11 ± .017 (7)	.26 ± .027 (7)
Prostrate knotwood (*Polygonum aviculare*)	.28 ± .024 (9)	1.38 ± .093 (9)	.11 ± .013 (3)	.23 ± .042 (4)
Draba (*Draba* spp.)	—	.18 ± .031 (2)	.08 ± .005 (3)	.06 ± .000 (1)
Common fireweed (*Epilobium angustifolium*)	—	—	.02 ± .002 (2)	.08 ± .016 (3)
Aster (*Aster* spp.)	—	—	.24 ± .000 (1)	—
Common dandelion (*Taraxacum officinale*)	—	—	.06 ± .000 (1)	—
Lodgepole pine (*Pinus contorta*)	—	—	.12 ± .016 (4)	.06 ± .000 (3)

[1]Values are mean ± S.E.
[2]Number of observations.

grasses. The apparent absence of slender wheatgrass from the study plots in year 1 may have resulted from sampling error; seedlings were extremely difficult to identify during the first year, and slender wheatgrass may have been misidentified or placed in an *Agropyron* species category. Spike trisetum was not observed in the sample plots in year 1 or year 3. Both muttongrass and tufted hairgrass were present in a high number of sample plots in year 3. The seeded native forbs all occurred in the study plots by year 3, but only western yarrow was found in a high number of sample quadrats. Establishment of the seeded native shrubs was poor with only a few individuals of Saskatoon serviceberry and Woods rose occurring in the sample plots. Colonizer dominants in year 1 were alkali sandspurry, spreading groundsmoke, and prostrate knotweed. By year 3 individuals of winter bentgrass, draba, common fireweed, aster, common dandelion, and lodgepole pine were also recorded.

In general, the effects of fertilizer on individual species were the same as those observed in the combined species analyses. Standing crop biomass of most species was higher in fertilized than in unfertilized plots in year 1. In year 3 standing crop biomass was either less in fertilized than in unfertilized plots or exhibited a relatively lesser increase in fertilized than in unfertilized plots.

Cover

Results of the cover data analysis followed the same trends as those of the standing crop biomass analysis (fig. 3). There were no significant differences in the cover classes that were attributable to grass seeding density. Fertilization resulted in higher vegetation cover and lower bare ground cover in the combined 3-year analysis (both, $p < 0.001$). Differences existed among years for all of the cover classes, except vegetation ($p < 0.05$ to $p < 0.001$). The response to fertilizer was not consistent over time. In treatments that were unfertilized, vegetation cover increased between years 1 and 3, while litter and bare ground remained unchanged and rock increased ($p < 0.05$). Treatments that were fertilized showed significant yearly decreases in vegetation cover and increases in litter, bare ground, and rock ($p < 0.05$).

Soil Properties

Two years after the study plots had been fertilized, there were no significant differences in either soil NO_3–N or exchangeable K between fertilized and unfertilized treatments (table 3). However, significantly higher levels of available P existed in fertilized than in unfertilized treatments ($p < 0.01$).

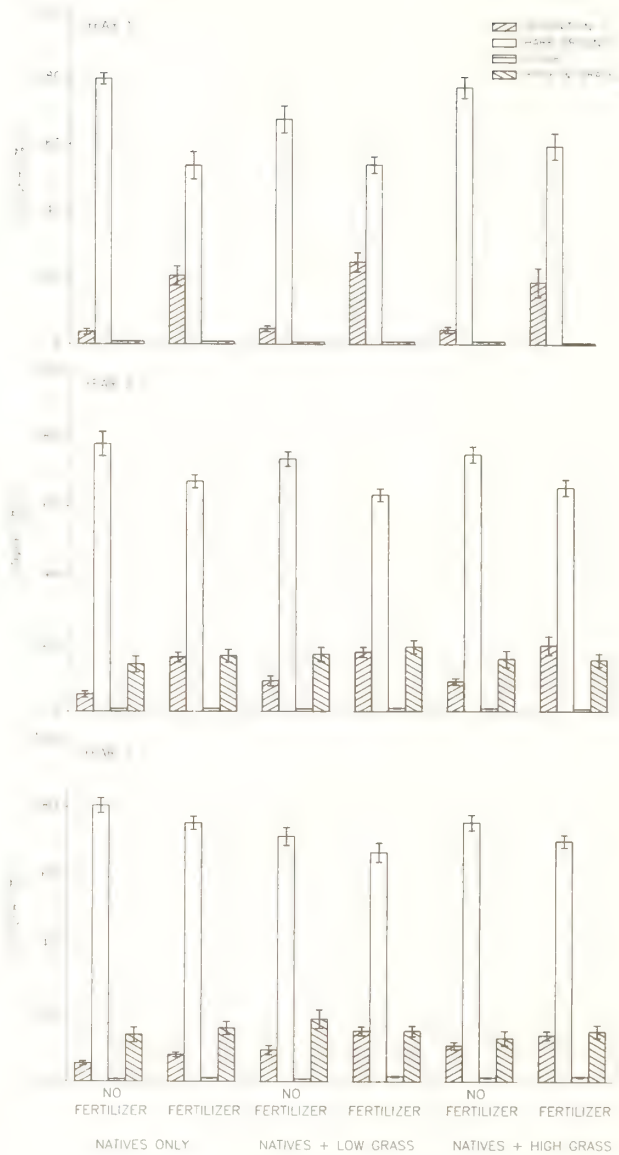

Figure 3—Percentage cover by cover class for 1985, 1986, and 1987 in research plots that were seeded with natives and a zero, low, or high level of introduced grasses and then either fertilized or not fertilized. Values are mean ± S.E., $n = 30$.

Table 3—Levels of soil nutrients on the study plots 2 years after fertilization

Variable	Fertilized	Not fertilized	
NO_3–N (mg/kg)	[1]5.8 ± 0.22	5.8 ± 0.14	NS[2]
P (mg/kg)	26.7 ± 2.74	18.0 ± 1.31	0.01
K (mg/kg)	66.1 ± 4.08	66.3 ± 3.37	NS

[1]Values are mean ± S.E., $n = 9$.
[2]Significance levels for differences between treatments from ANOVA's.

DISCUSSION

This section discusses the three null hypotheses I set out in the Introduction section. Also, reclamation strategies based on the research may prove helpful to land managers.

Hypothesis 1

Increasing density of introduced grasses did not lower establishment or growth of the native species. These findings are contrary to those of studies in which higher seeding densities have decreased species diversity due to increased interspecific competition and competitive exclusion of less "vigorous" native species (Holecheck and others 1981). The results of the current study may be partly explained by the poor establishment of seeded species in general. Densities of the introduced grasses and natives may have been insufficient for significant competitive interactions to occur. The colonizers did exhibit decreases in standing crop with increases in grass seeding density and may have been more sensitive to the competitive effects of the introduced grasses than the native species. In turn, the abundance of the colonizer, alkali sandspurry, in year 1 may have negatively affected establishment of both introduced grasses and native species.

The high variability in species establishment may have been related more to establishment requirements and site characteristics than to introduced grass seeding density. The saturated soils of the study area early in the growing season may have favored germination and establishment of species adapted to moister edaphic conditions. Tufted hairgrass, muttongrass, and western yarrow occur on both disturbed areas and semiwet meadows near the study site and established in relatively high densities. Species such as spike trisetum, antennaria, silky phacelia, Saskatoon serviceberry, and mountain big sagebrush exist as colonizers on disturbed areas but almost never occur in semiwet meadows. The poor establishment of these species may indicate a low tolerance to saturated soils.

Hypotheses 2 and 3

Fertilization did not have a larger positive effect on the 3-year establishment and growth of the introduced grasses than of the native species. Because increasing introduced grass density had no effect on native species establishment, hypothesis 3 could not be tested. Introduced grasses, native species, and colonizers all showed large initial responses to fertilizer. However, after levels of soil nutrients had decreased in the fertilized treatments, introduced grasses exhibited a larger relative decrease in standing crop biomass than native species, and colonizers had the largest decrease of all. In the unfertilized treatment, native species had greater increases in standing crop biomass than introduced species. Perennial introduced grasses frequently exhibit rapid growth rates and high nutrient uptake efficiencies but maximum expression of these characteristics is obtained only at relatively high nutrient levels (Chapin 1980). Thus, these species show large responses to fertilizers but require sustained nutrient levels to maintain high levels of productivity. Many native species are adapted to lower nutrient levels and exhibit slower growth rates and lower nutrient uptake efficiencies (Chapin 1980). In general, they show smaller responses to fertilizers and can maintain productivity, albeit at lower levels, with lower levels of nutrients.

The pattern of rapid invasion followed by precipitous decline exhibited by the colonizer, alkali sandspurry, has been observed in other ecosystems for different species (Allen and Allen 1984; Allen and Knight 1984; Redente and Cooke 1986). Immediately following disturbance, availability of nutrients, especially N, can be high depending upon the type of disturbance and the stage of soil development (Tilman 1985; Vitousek and others 1979). Fertilization during reclamation can exacerbate these results. Many early successional species exhibit rapid establishment and growth during this phase, but are rapidly excluded as levels of nutrients decrease and competition from later successional species increases.

The rapid decline in plant available N and K was largely determined by soil nutrient dynamics. A portion of the nutrients added to the site through fertilization may have been taken up by the colonizer species in year 1 and tied up in their undecomposed litter in years 2 and 3. However, the soil on the site had inherently low nutrient retention capacity as characterized by a high portion of coarse materials (33.5 percent), low cation exchange capacity (3.2 meq/100g), and low amount of organic matter (0.4 percent). Precipitation in the study area is relatively high and may contribute to low retention of mobile nutrients. Fertilization of these soils resulted in a pulse of nutrients to the system during the first growing season followed by a rapid decline in the mobile nutrient N and to a lesser extent K. Phosphorus is less mobile and higher levels were maintained over time.

Reclamation Strategies

Methods used in the reclamation of nutrient deficient soils, such as those in this study, should be determined by the site's inherent regenerative capacity and the desired end land use. If the objective of revegetation of similar drill pad sites in the area is reestablishment of lodgepole pine, and if relatively low biomass production of grasses and forbs is acceptable in the interum, then fertilization may not be necessary and species adapted to low levels of nutrients should be seeded. Fertilization of nitrogen deficient soils does not alter the soil characteristics or decrease the deficiency (Bloomfield and others 1982). This and other studies (see Chapin 1980) indicate that native species adapted to low nutrient conditions can maintain more constant productivity on low nutrient soils than high-nutrient adapted introduced species. The N status of nutrient deficient soils has often been improved by seeding species with nitrogen-fixing symbionts (Bloomfield and others 1982; Jeffries and others 1981). A legume, northern sweetvetch (*Hedysarum boreale*), performed well in separate study plots on the site and may be beneficial on similar sites. On sites with P or micronutrient deficiency, fertilization with these elements may increase establishment and productivity.

If the objective in revegetating these sites is to increase biomass production of grasses or forbs and to perhaps slow reestablishment of lodgepole pine, then treatments that increase the nutrient retention capacity of the soil and accelerate the development of a viable nutrient cycle may be necessary. Topsoil is typically used in revegetation to provide a growing medium and to accelerate soil development. However, addition of selected organic amendments may be equally or more effective in soil development than more expensive topsoil/mulch procedures (Elkins and others 1984; Scholl and Pace 1984; Woods and Schuman 1986). Once the nutrient retention capacity of the soil has been improved, it is possible to seed a higher proportion of high-nutrient adapted species and thereby increase biomass production. In addition, on sites with relatively greater nutrient retention capacities, fertilization may have a larger effect on plant establishment and production. Including low-nutrient adapted species and species with N-fixing symbionts on these sites will increase species diversity and may still help to ensure their sustained productivity.

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This study examined the effects of introduced grass seeding density and fertilizer on native species establishment on an oil drill pad site in the Uintah Mountains, UT. Differences in first-year seedling density and 3-year standing crop biomass among treatments were evaluated for seeded introduced grasses and native species and for unseeded colonizers. Aerial cover was measured all 3 years and the effects of fertilization on soil NO_3—N, available P, and exchangeable K were examined 2 years after application. Recommendations for reclamation of similar sites are given.

KEYWORDS: reclamation, revegetation, fertilization, seeding density, introduced grasses

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Test of RPA Production Coefficients and Local Assumptions for the Pinyon-Juniper Ecosystem in Central Utah

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RESEARCH SUMMARY

The Oak Creek Mountain Range Evaluation Area and other similar evaluation areas were established as part of the Accelerated Range Program of the Forest Service, U.S. Department of Agriculture. One of the purposes was to field test production assumptions, such as those for herbage and shrubs, developed in response to the Resources Planning Act (RPA). Production assumptions from an environmental statement and a soils report were also available for comparison. Four areas of pinyon-juniper removal and forage plant seeding, treated in 1955, 1977, 1978, and 1980 respectively, were studied over a period of 8 years. Although precise positioning of the Oak Creek area within the RPA pinyon-juniper coefficient matrix was difficult, current data and published information support a conclusion that herbage and shrub production assumptions in the RPA scenario and the local soil report were unrealistically high. The estimate provided by the environmental statement for chaining on Utah National Forests was the most accurate.

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INTRODUCTION

The 1970 study "The Nation's Range Resources—A Forest-Range Environmental Study" evaluated forests and rangelands in the 48 adjacent United States to determine the current and potential future production of animal unit months (AUM's) of grazing and for associated products and benefits (Forest-Range Task Force 1972). The information was used to construct alternate sets of management goals for range livestock production and to evaluate costs. In response to the study the Chief of the Forest Service, U.S. Department of Agriculture, began the Accelerated Range Program in 1973. This program included a system of large-scale evaluation areas originally conceived to test assumptions of the Forest-Range Task Force and were to be a basis to make appropriate adjustments in the Accelerated Range Program (Sanderson and others 1988). These evaluation areas also were to serve as a basis to test rangeland management production and cost assumptions developed in response to the Forest and Rangeland Renewable Resources Planning Act of 1974 (RPA). A secondary purpose was to provide local demonstrations of range improvement practices.

Evaluation areas were established in the Northwest, the South, and in central Utah of the Intermountain Region. The area in Utah, termed the "Oak Creek Mountain Range Evaluation Area," was established in 1978 to provide information on overall effectiveness of range management practices within the pinyon-juniper (*Pinus edulis, P. monophylla, Juniperus osteosperma*) ecosystem. The project emphasized the necessity of and benefits from coordinated planning and action between Federal, State, and local agencies, as well as private landowners. Despite disruptions caused by two large wildfires, thousands of acres of revegetation work was completed (Pope and Wagstaff 1987).

The basic revegetation effort on the Oak Creek area, excluding fire rehabilitation, was the conversion of specific areas of pinyon-juniper woodland to grass-dominated plant communities to improve forage supplies. The objective of this study was to provide a field test of the specific local and RPA assumptions of herbage and shrub production in the pinyon-juniper ecosystem.

STUDY AREA

The Oak Creek Mountain Range Evaluation Area encompasses 316,000 acres about 15 miles north of Fillmore, UT. The topography is highly variable ranging from desert-shrub flats at the 4,800-foot elevation through rolling foothills and benches to steep rocky peaks that exceed 9,700 feet. The pinyon-juniper zone begins at 5,200 to 5,600 feet elevation with an upper limit of about 8,000 feet on south exposures and up to about 6,000 feet on north exposures. The sagebrush zone is intermingled with the pinyon-juniper zone. Vasey big sagebrush (*Artemisia tridentata* ssp. *vaseyana* is most abundant (Goodrich 1984).

The climate is typical for the Great Basin, with cold, moist winters and warm, dry summers. The average long-term precipitation at the Oak City weather station near the lower edge of the pinyon-juniper zone is 12.06 inches. Average precipitation of most of the pinyon-juniper area included in this study is approximately 13 to 15 inches annually (U.S. Department of Agriculture-U.S. Department of the Interior 1981). Precipitation at the Oak City weather station shows rainfall was 119 to 159 percent of normal in the years of measurement (table 1).

Specific study sites at Oak Creek included new treatments and areas that had been treated in earlier years. Data were obtained from four field situations: Church Hills chaining of 1980, Clay Springs chaining of 1978, Eight-Mile chaining of 1977, and Eight-Mile cabling of 1955. The Church Hills chaining consisted of six study areas of 80 to 200 acres each; three were chained and three were left as untreated controls. Ten transects of 10 plots each were established per area. The plots were circular, 9.6 ft^2 in area, and located 66 feet apart on the transects. Weight estimates were made on the plots for each grass, forb, and shrub species. Two additional plots per transect were estimated then clipped, ovendried, and weighed to determine correction factors for conversion to dry weight. Twelve transects were located in the Clay Springs chaining before treatment with the intent that three would be in untreated areas. However, after the planned treatment and an unplanned wildfire, one transect could not be relocated and no transect remained

Table 1—Precipitation at Oak City for those years when tree removal and seeding or vegetation sampling occurred

Month	Year										
	1955	1956	1977	1978	1979	1980	1981	1982	1983	1984	1985
January	1.55	2.47	0.86	2.60	1.43	2.23	0.72	1.27	0.82	0.78	0.90
February	2.16	.92	12	2.00	1.42	2.62	.22	.29	1.64	1.05	1.03
March	0.15	06	1.09	2.74	2.03	3.39	1.60	1.62	2.82	2.54	1.47
April	.30	.86	.24	2.51	.93	.65	2.20	.74	2.45	1.82	.78
May	99	.82	1.54	1.62	1.51	3.20	2.85	1.44	1.47	.54	1.88
June	1.48	.28	.35	.08	.91	.00	.30	.36	.58	2.54	1.71
July	74	61	1.16	09	.10	.47	.20	.78	33	2.44	.84
August	77	51	.84	.91	.76	32	49	1.33	2.08	1.58	00
September	.75	.04	59	2.43	00	1.83	1.96	5.01	1.48	1.17	1.27
October	.28	1.00	.73	.27	1.44	1.63	4.07	2.31	1.02	2.56	1.31
November	.82	.05	30	2.90	1.31	1.33	1.23	.93	3.10	1.09	1.84
December	.56	.13	.76	1.01	.43	.32	.95	2.18	2.44	1.26	1.35
Calendar year	10.55	7.75	8.58	19.16	12.27	17.99	16.79	18.26	20.23	19.37	14.38
Crop year [1]	—	7.82	5.42	13.93	14.84	15.27	13.00	13.93	20.21	17.31	13.85
Yield index [2]	—	72	42	145	156	161	133	145	221	186	144

[1] Crop year = September to June (Sneva and Britton 1983).
[2] Yield index = expected plant production level compared to a crop year with median precipitation (Sneva and Britton 1983).

Table 2— Years of sampling on the four Oak Creek study sites

Site	Year				
	1978	1980	1981	1982	1985
Church Hills					
Treated				X	X
Untreated (or control)		X		X	X
Clay Springs					
Treated		X			X
Untreated (or control)	X				
Eight-Mile 1977					
Treated		X		X	X
Untreated (or control)					
Eight-Mile 1955					
Treated		X	X		X
Untreated (or control)					

with an intact overstory. The Eight-Mile study sites were established in two areas previously cleared of trees and seeded to herbaceous species—one in 1955 and one in 1977. Twenty sample locations were equally distributed among swale bottom, side slope, and ridge crest topography on a generally south aspect to study forage production potential of the three slope positions. Each sample location consisted of two transects of 10 plots each.

Although measurement of plant production was conducted in 3 years on each of the study areas, the sampling was spread over an 8-year period due to timing of seeding, grazing rotations, and so forth (table 2). Sampling was conducted only when individual areas were in a rested or deferred grazing situation. The areas were treated in different years (were of different ages), and data were collected in different sets of years. Although differences in planting technique, weather, and site contribute to variation in the field data, the results provide a basis for interpretation of trends.

PRODUCTION ASSUMPTIONS

Production assumptions were garnered from one national source—the RPA management scenario—and local sources—National Forests' environmental statement and a soil survey.

National RPA Assumptions

The RPA management scenario prepared for the pinyon-juniper ecosystem described four productivity classes subdivided by condition class and range management strategy (table 3). A copy of RPA management scenarios and assumptions is on file at the Forestry Sciences Laboratory, Boise, ID. The management strategy of the Oak Creek area was similar to strategy D of the scenario. This consisted of intensive management to increase livestock forage consistent with constraints of maintaining the environment and providing for multiple use. Practices such as pinyon-juniper removal and seeding with forage species were a part of this strategy, as were the installation of fencing and water developments to obtain a more uniform distribution of livestock.

No definition or description of the condition classes was provided in the scenerio. Desirable perennial forage plants on the study sites before treatment made up only 13 to 40 percent of the herbage and shrub production, and the density of the tree stand limited the herbage and shrub understory production to about 100 lb per acre.

Assumptions for National Forests

In the chaining environmental statement, the assumption for change in herbage ("forage") production was an increase of 500 to 700 lb per acre "under favorable conditions" on National Forests in Utah after removal of pinyon-juniper stands (USDA 1973).

Table 3—RPA assumptions for herbage and shrub productivity for the D level management strategy

Productivity class	Condition class	Pounds per acre per year
1 High	1 Good	1,200
	2 Fair	1,100
	3 Poor	1,000
	4 Very poor	800
2 Mod. high	1	1,000
	2	900
	3	800
	4	700
3 Med. low	1	700
	2	600
	3	500
	4	400
4 Low	1	300
	2	200
	3	100
	4	100

Assumptions Based on a Soil Survey

A contract soil survey report prepared for the Forest Service provided estimates of potential vegetation productivity (Stoneman and others 1979). The production of air-dry vegetation in pounds per acre was estimated for both unfavorable (less than average precipitation) and favorable (greater than average precipitation) years. The soils of three study areas had similar estimated herbage and shrub productivity—660 lb per acre in unfavorable years and 1,415 lb per acre in favorable years. The estimates for the Clay Springs area were less—460 and 780 lb/acre—apparently because of the sandy eolian soils that were poorly developed and excessively drained.

VEGETATION TREATMENT

The three most recent vegetation treatments were similar in that the trees were removed by pulling an anchor chain between two crawler tractors and the areas were seeded from the air. The areas were chained a second time to cover the seed and to improve the effectiveness of tree removal.

The seed mixture for the Church Hills chaining was:

Crested wheatgrass (*Agropyron cristatum* and *A. desertorum*)	2.0 lb per acre
Intermediate wheatgrass (*A. intermedium*)	0.6
Pubescent wheatgrass (*A. trichophorum*)	0.6
Russian wildrye (*Elymus junceus*)	1.2
Hard sheep fescue (*Festuca ovina* ssp. *duriuscula*)	0.2
Ladak alfalfa (*Medicago sativa* var. *ladak*)	1.2
Yellow sweetclover (*Melilotus officinalis*)	0.2
Small burnet (*Sanguisorba minor*)	2.0
Total	8.0 lb per acre

A small amount of bitterbrush (*Purshia tridentata*), cliffrose (*Cowania mexicana*), and fourwing saltbush (*Atriplex canescens*) seed was also applied by dribblers on the crawler tractors during the second chaining.

The seed mixture for the Clay Springs chaining was:

Crested wheatgrass	2.6 lb per acre
Intermediate wheatgrass	4.0
Pubescent wheatgrass	1.5
Russian wildrye	0.8
Smooth brome (*Bromus inermis*)	2.9
Indian ricegrass (*Oryzopsis hymenoides*)	0.1
Total	11.9 lb per acre

Some browse seed was also applied by a dribbler on one of the tractors.

The 1977 treatment portion of the Eight-Mile area was seeded with:

Crested wheatgrass	2.5 lb per acre
Intermediate wheatgrass	6.3
Pubescent wheatgrass	1.2
Ladak alfalfa	0.5
Total	10.5 lb per acre

In addition, about 0.2 lb per acre of bitterbrush seed was applied by dribbler.

The oldest treatment area (1955) was cabled twice, and the slash was bunched into windrows with a small crawler tractor. Wheatgrasses were seeded on the area, but the sequence of procedures and detail of seed mixtures are not known.

RESULTS

Data were collected from all treatment areas the final year of study (1985). Table 4 presents these data by species to illustrate composition of the plant communities at the end of the study. The older treatment sites (Eight-Mile area) were strongly dominated by introduced wheatgrasses. They made up 91 percent of the composition in the 1955 treatment area and 71 percent in the 1977 treatment area. Intermediate and pubescent wheatgrasses were most prevalent followed by crested wheatgrass. These grasses so dominated the site that only a limited amount of shrubs were present and there were few forbs. The Clay Springs and Church Hills areas, which were treated as part of the Oak Creek Mountain Range management program, had less dominance by seeded grasses—60 and 44 percent, respectively. Western wheatgrass (*Agropyron smithii*), bluebunch wheatgrass (*A. spicatum*), and Indian ricegrass—desirable native perennial grasses—were more apparent in the composition. A greater variety of both forbs and shrubs were also present in the areas more recently treated.

Table 4—Data (lb per acre) collected in 1985 from the four pinyon-juniper treatment areas

	Eight-Mile 1955 treatment			Eight-Mile 1977 treatment					
	Slope position			Slope position					
	Swale Bottom	Side Slope	Ridge Crest	Swale Bottom	Side Slope	Ridge Crest	Clay Springs	Church Hills Treated	Church Hills Untreated
Grasses									
Agropyron cristatum	60.7	175.0	123.5	274.8	167.0	291.3	153.1	123.1	0.3
Agropyron intermedium	389.7	247.3	193.3	416.5	373.7	153.0	42.1	88.1	.0
Agropyron smithii	24.0	.0	0	7.8	0	.0	12.2	11.1	2.2
Agropyron spicatum	.0	6.0	27.3	5.8	51.3	95.3	70.8	98.9	21.6
Agropyron trichophorum	363.0	197.7	140.0	155.5	51.3	34.3	46.2	26.0	.3
Bromus inermis	.0	.0	.0	.3	3.0	1.3	43.0	1.4	.0
Bromus tectorum	.3	.3	.8	.3	8.0	5.3	53.0	9.1	18.1
Dactylis glomerata	.0	.0	0	.0	.0	.0	.0	1.7	.0
Elymus junecus	.0	.0	0	.0	0	.0	.0	2.0	.0
Oryzopsis hymenoides	.0	.0	.0	.0	.0	.0	8.9	13.2	4.0
Poa bulbosa	2.7	2.3	1.8	40.0	0	1.7	.0	.0	.0
Poa fendleriana	.0	.0	.0	.0	0	0	.0	.0	.1
Poa secunda	8.0	6.7	3.5	8.0	24.3	7.7	9.7	3.2	17.8
Sitanion hystrix	.0	.0	.0	.1	.3	1.0	1.1	5.3	3.6
Stipa comata	.0	.0	.0	.0	.0	3.0	0	1.7	.5
Forbs									
Agoseris glauca	.0	.0	0	.0	0	1.0	.0	3	T
Allium acuminatum	.0	.0	.0	.0	.0	T	.0	T	.2
Alyssum desertorum	.0	.0	.0	.0	.0	.1	.0	T	.3
Antennaria dimorpha	.0	.0	.0	.0	T	.4	.0	.1	.1
Arabis holboelii	.0	.3	.0	.0	.0	.0	.0	.2	T
Arenaria kingii	.0	.0	.0	.0	.0	.0	.0	.1	T
Astragalus cibarius	.0	.0	.0	.3	.1	.0	.0	.0	.0
Astragalus convallarius	0	.0	1.8	.0	.0	.0	.0	2.0	1.6
Astragalus eurekensis	0	.0	0	0	0	0	.0	.2	.7
Astragalus utahensis	0	.0	0	.0	1	.0	.0	.0	.0
Calochortus nuttallii	.0	.0	0	.1	3	2.3	.0	.3	.7

(con.)

Table 4 (Con.)

	Eight-Mile 1955 treatment			Eight-Mile 1977 treatment					
	Slope position			Slope position					
	Swale Bottom	Side Slope	Ridge Crest	Swale Bottom	Side Slope	Ridge Crest	Clay Springs	Church Hills Treated	Church Hills Untreated
Camelina microcarpa	.0	.0	.0	T	.0	0	.0	.1	2
Castilleja chromosa	.0	.0	.0	.0	.0	.3	.0	.1	0
Chaenactis douglasii	.0	.0	0	.0	T	7	0	4 7	4 0
Collinsia parviflora	.0	.0	.0	T	.3	T	.0	.2	.4
Comandra pallida	0	.0	.0	.0	0	.0	0	2.7	.0
Cryptantha humilis	.0	.0	.0	.1	0	.7	.1	.1	1.6
Descurainia pinnata	.0	T	.0	.0	.8	T	T	1.2	1
Draba cuneifolia	.0	.0	T	T	T	T	T	1	.2
Epilobium paniculatum	.0	.0	.0	.0	.3	.0	.0	T	T
Erigeron pumilus	.0	.0	.0	.0	0	.0	0	.1	T
Eriogonum cernuum	.0	.0	.0	.0	.0	.0	.1	T	T
Eriogonum ovalifolium	.0	.0	.0	.0	.7	0	.0	.0	0
Eriogonum racemosum	.0	.0	.0	.0	7	.0	.3	.0	.0
Eriogonum umbellatum	.0	.0	0	.0	3	0	.0	6.3	2.3
Erodium cicutarium	.0	.0	.0	.0	.0	.1	T	0	.0
Gayophytum spp.	.0	.0	.0	.0	.1	1	0	.1	0
Gilia aggregata	.0	0	.0	.0	.0	0	0	1	T
Gilia inconspicua	.0	.0	0	0	T	.7	0	.1	2
Lactuca serriola	.0	0	.0	3	5.0	.7	3.2	15.0	4.5
Linum lewisii	.0	.0	.0	0	0	4 7	0	.8	.0
Lithospermum incisum	.0	0	.0	.0	0	0	0	.3	2
Lomatium grayii	.0	.0	5	0	1 3	0	.0	0	.1
Machaeranthera canescens	.0	.0	.0	.0	0	.0	.1	.4	.2
Medicago sativa	.0	.0	.0	47.3	60.7	.0	T	9 1	.0
Microsteris gracilis	T	T	.1	T	.3	.2	T	.4	.3
Penstemon humilus	.0	.0	.0	1.0	.1	.0	.0	2.8	1.4
Petradoria pumila	.0	.0	.0	.0	2 3	5.7	.0	7.0	1.6
Phlox hoodii	.0	.0	11.0	.0	.0	.0	.0	.1	.4
Phlox longifolia	.0	.0	.0	.0	0	0	0	T	6
Physaria chambersii	.0	.0	.1	.0	8	0	0	1	.6
Psoralea lanceolata	0	.0	0	0	0	0	5	0	0
Ranunculus testiculatus	T	T	T	T	T	T	T	.1	8
Salsola kali	.0	.0	.0	0	0	.0	0	.2	0
Sanguisorba minor	0	.0	.0	.0	0	T	.0	20.3	0
Sisymbrium altissimum	.0	.0	.0	.0	0	0	13.2	T	.0
Sphaeralcea coccinea	.0	.0	.0	.0	T	.0	.0	4	7
Sphaeralcea grossulariaefolia	.0	.0	.0	.0	.0	.0	.1	.8	.0
Streptanthus cordatus	.0	.0	T	.0	1.3	.1	.0	1.3	.2
Tragopogon dubius	.0	T	.0	.3	1.0	5	.0	9.5	1 5
Vicia americana	.3	.0	T	2.0	.7	.1	.0	.7	2.9
Shrubs									
Artemisia nova	.0	0	.0	.0	0	0	0	8.8	1 0
Artemisia tridentata	4.0	3	4.0	104.8	106.7	24.0	11.3	23.5	28.1
Chrysothamnus viscidiflorus	.0	T	27.3	9.0	.0	29.3	.1	3.4	.6
Cowania mexicana stransburiana	.0	.0	.0	0	16.7	1.0	.0	1 4	4
Eriogonum microthecum	.0	.0	.0	0	0	.0	.0	1 4	2
Leptodactylon pungens	.0	.0	1.3	.0	0	1.0	0	3 3	1 2
Purshia tridentata	.0	.0	.0	1.5	4 3	.7	3.4	4.9	6 9
Tetradymia canescens	.0	.0	.0	.0	.0	.0	.0	.7	.0
Xanthocephalum sarothrae	.5	6.3	19.0	34.3	8.7	15.7	3.1	28.5	25.7

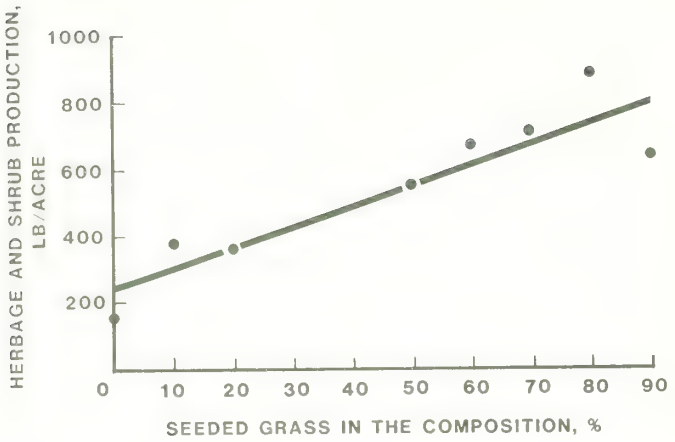

Figure 1—Relationship of percent seeded grassses and total production.

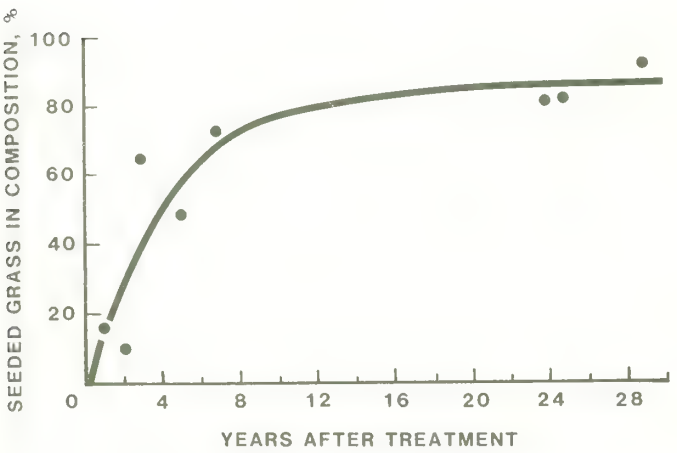

Figure 2—Percent seeded grasses and year after treatment.

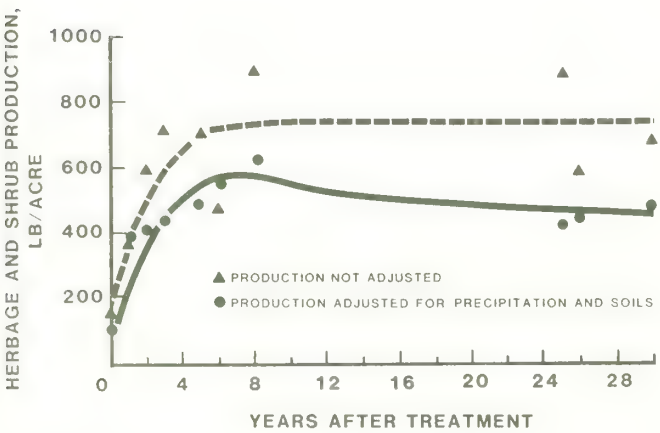

Figure 3—Production time trend.

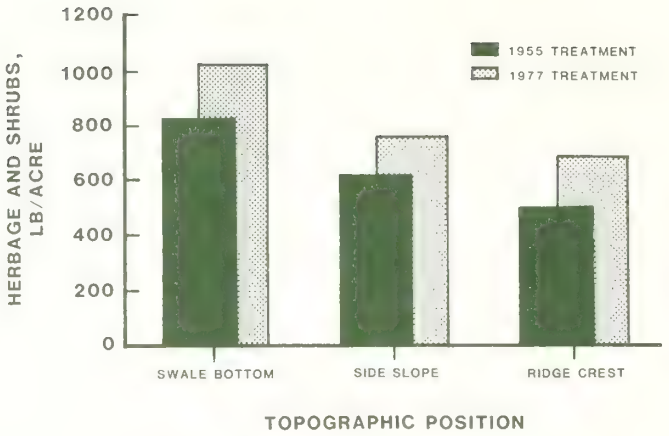

Figure 4—Effect of topography on herbage and shrub production. Bars represent a mean for 3 years of data.

Total production was closely correlated to the proportion of the seeded wheatgrasses (fig. 1). This suggests that many of the other plants present following tree removal, both natives and exotics, are inefficient in the use of the existing site productivity, or at least they are slow in developing the densities necessary to fully utilize the site. The older stands tended to be dominated by intermediate and pubescent wheatgrasses that are rhizomatous and sod-formers (Asay and Knowles 1985; Wasser 1982). These seeded grasses have the capability to increase stand densities over time by vegetative means. The data from Oak Creek suggest that about 8 to 10 years are required for these grasses to reach a stable proportion of the composition, which may be over 80 percent (fig. 2). Similar to this trend, the total production of herbage and shrubs appeared to increase for as much as 8 years (fig. 3). Previous results from the Utah area have demonstrated that the level of total herbage production in the early years after seeding is strongly affected by the proportion of seeded grass in the plant community (Clary and Wagstaff 1987; Phillips 1977).

There was a substantial difference among swale bottom, side slope, and ridge crest areas of topography (fig. 4, tables 5 and 6). Herbage and shrub production in the swale bottom portions of the topography with its deeper soil and more favorable soil moisture condition was a third and two-thirds greater than the side slope and ridge crest portions of the area, respectively.

Comparison With Assumptions

The RPA assumptions for herbage and shrub production under intensive management vary from 1,200 down to 100 lb per acre depending upon productivity class and condition class (table 3). The older treatment areas, considered to represent the long-term production potential for seeded stands, have a strong dominance of seeded grasses and therefore were considered in "good" condition. These areas (tables 5 and 6) averaged 740 lb per acre of herbage and shrub production with a 95 percent

Table 5—Herbage and shrub production by slope position on the 1955 Eight-Mile treatment area

Vegetation	1980			1981			1985		
	Swale Bottom	Side Slope	Ridge Crest	Swale Bottom	Side Slope	Ridge Crest	Swale Bottom	Side Slope	Ridge Crest
Grasses									
Perennial									
Seeded	[1]836 ± 77	592 ± 57	285 ± 52	662 ± 47	444 ± 24	340 ± 65	813 ± 149	620 ± 115	457 ± 89
Native	35 ± 9	61 ± 21	53 ± 19	50 ± 50	56 ± 27	24 ± 13	32 ± 22	13 ± 10	31 ± 30
Annual	11 ± 4	33 ± 26	31 ± 22	15 ± 15	1 ± 1	2 ± 2	2 ± 1	3 ± 2	3 ± 1
Forbs	13 ± 9	3 ± 1	13 ± 5	9 ± 5	1 ± 1	34 ± 26	0 ± 0	0 ± 0	13 ± 12
Shrubs	7 ± 3	12 ± 7	77 ± 24	7 ± 4	21 ± 11	94 ± 20	5 ± 4	7 ± 3	52 ± 27
Total	902 ± 74	701 ± 43	459 ± 32	743 ± 25	523 ± 24	494 ± 48	852 ± 168	643 ± 113	556 ± 31
Median[2] year estimate	560	435	285	559	393	371	592	446	385

[1]Pounds per acre $\bar{x} \pm s.e.$
[2]Estimated herbage and shrub production under conditions of median September to June precipitation (Sneva and Britton 1983).

Table 6—Herbage and shrub production by slope position on the 1977 Eight-Mile treatment area

Vegetation	1980			1982			1985		
	Swale Bottom	Side Slope	Ridge Crest	Swale Bottom	Side Slope	Ridge Crest	Swale Bottom	Side Slope	Ridge Crest
Grasses									
Perennial									
Seeded	[1]747 ± 106	376 ± 83	307 ± 79	636 ± 68	379 ± 86	321 ± 58	847 ± 118	595 ± 83	480 ± 135
Native	66 ± 20	157 ± 36	144 ± 47	48 ± 14	119 ± 34	164 ± 65	22 ± 6	76 ± 53	107 ± 66
Annual	62 ± 8	33 ± 8	54 ± 12	129 ± 23	114 ± 39	203 ± 26	40 ± 40	8 ± 8	7 ± 4
Forbs	16 ± 7	15 ± 3	14 ± 4	41 ± 20	42 ± 27	17 ± 4	51 ± 28	77 ± 38	20 ± 15
Shrubs	54 ± 18	40 ± 16	37 ± 12	160 ± 47	103 ± 40	108 ± 34	150 ± 61	136 ± 72	72 ± 38
Total	945 ± 89	621 ± 48	556 ± 33	1,014 ± 42	757 ± 65	813 ± 66	1,110 ± 109	892 ± 71	686 ± 105
Median[2] year estimate	588	386	346	699	523	560	770	620	476

[1]Pounds per acre $\bar{x} \pm s.e.$
[2]Estimated herbage and shrub production under conditions of median September to June precipitation (Sneva and Britton 1983).

confidence limit of 680 to 800 lb per acre. The more recent seedings, for purposes of this evaluation, were considered in "fair" condition within the RPA matrix because of less dominance of seeded species. These sites produced approximately 530 lb per acre (tables 7 and 8) with a confidence limit of 490 to 570 lb per acre. The herbage and shrub production appeared, therefore, to average about 110 to 220 lb per acre less than expected for a site of average productivity, about 260 to 370 lb per acre less than expected for a site of moderately high productivity, and 460 to 570 lb per acre less than expected for a site of high productivity (table 9).

Precipitation in the Oak Creek area was above average from the late 1970's to the last year of production measurements, 1985. At Oak City, precipitation averaged 140 percent of normal during the years the older seedings were sampled (used as a basis for long-term productivity estimates). Because average precipitation for the study area was estimated to be 13 to 15 inches per year (U.S. Department of Agriculture-U.S. Department of the Interior 1981), a 40 percent increase during measurement years would have resulted in precipitation averaging approximately 20 inches. This is near the upper end of the range of average precipitation—8 to 22 inches—for the pinyon-juniper ecosystem (Clary 1987). Soil depths of 11 to 20 inches (Stoneman and others 1979; and RPA scenario) also suggest the Oak Creek area should be above average in plant production potential for the pinyon-juniper ecosystem. If we assume that during these years the study areas should have exhibited "moderately high" productivity (1,000 lb per acre under good condition), the general production levels are approximately one productivity class lower than suggested by the RPA assessment. Only the "swale bottom" topographic position (measured in the older seedings) had sufficient production (average of 928 lb per acre from tables 5 and 6) to approach expectations from the RPA matrix. In addition, the swale bottoms are actually more representative of big sagebrush site inclusions than pinyon-juniper sites, as such.

Table 7—Herbage and shrub production before (1978) and after (1980, 1985) treatment at Clay Springs

Vegetation	Year 1978	1980	1985
Grasses			
Perennial			
Seeded	[1]0 ± 0	55 ± 16	284 ± 69
Native	6 ± 2	89 ± 39	103 ± 53
Annual	12 ± 3	114 ± 17	53 ± 23
Forbs	9 ± 2	33 ± 2	18 ± 5
Shrubs	27 ± 12	67 ± 26	18 ± 8
Total	54 ± 15	358 ± 58	476 ± 76
Median[2] year estimate	37	222	331
Median year estimate adjusted to account for less productive soils[3]	62	370	552

[1] Pounds per acre $\bar{x} \pm s.e.$

[2]Estimated herbage and shrub production under conditions of median September to June precipitation (Sneva and Britton 1983).

[3]The Clay Springs soils were estimated to be 60 percent as productive as the remainder of the study area (Stoneman and others 1979).

Table 8—Herbage and shrub production for treated and control areas during pretreatment (1980) and posttreatment periods (1982, 1985) at Church Hills

Vegetation	1980 Chained	1980 Control	1982 Chained	1982 Control	1985 Chained	1985 Control
Grasses						
Perennial						
Seeded	[1]0 ± 0	0 ± 0	51 ± 10	0 ± 0	243 ± 25	1 ± 0
Native	42 ± 2	26 ± 2	122 ± 10	31 ± 4	133 ± 14	50 ± 5
Annual	21 ± 2	16 ± 2	173 ± 13	92 ± 10	9 ± 3	18 ± 4
Forbs	52 ± 3	40 ± 3	85 ± 12	14 ± 4	90 ± 10	31 ± 4
Shrubs	41 ± 4	51 ± 8	159 ± 19	113 ± 15	76 ± 13	64 ± 11
Total	156 ± 8	133 ± 12	590 ± 28	250 ± 18	551 ± 27	164 ± 18
Median[2] year estimate	98	83	408	174	383	114

[1]Pounds per acre, $\bar{x} \pm s.e.$

[2]Estimated herbage and shrub production under conditions of median September to June precipitation (Sneva and Britton 1983).

The assumptions from a more local viewpoint, developed in a Forest Service environmental statement on chaining of National Forest System lands in Utah (USDA FS 1973), project that an *increase* of 500 to 700 lb per acre due to chaining and seeding could be expected "under favorable conditions." If the average pretreatment production of 106 lb per acre is added to the assumed increase, the environmental statement projection is close (within 66 to 76 lb per acre) to the actual measured production (table 9). Production in the swale bottom topographic position exceeded the environmental statement assumption by 228 to 428 lb per acre.

The productivity assumptions made in the soil report (Stoneman and others 1979) were the furthest from reality. The estimates were about double the average measured production and even exceeded the production of the swale bottom topographic position of the older seedings by a substantial margin (~487 lb per acre) (tables 5, 6, and 9).

Another evaluation approach used was to approximate the production to be expected under normal precipitation. The production levels of the four study areas were adjusted to a median-precipitation-year basis by the methodology of Sneva and Britton (1983) (tables 5 to 8).

Table 9—Difference between assumptions and actual or adjusted data (pounds/acre)

Range	Actual production	RPA		Environmental statement		Soil report	
		Assumption	Difference from Actual	Assumption	Difference from Actual	Assumption	Difference from Actual
Good condition ranges							
High production	740	1,200	460	—	—	—	—
Moderately high production	740	1,000	260	[1]806	66	[2]1,415	675
Average production	740	850	110	—	—		
Moderately low production	740	700	(–)40	—	—	[2]780	40
Fair condition ranges							
High production	530	1,100	570	—	—		
Moderately high production	530	900	370	[1]606	76	—	—
Average production	530	750	220	—	—	—	—
Moderately low production	530	600	70	—	—	—	—
Data adjusted to represent good range condition and average soil and precipitation conditions	500	850	350	—	—	[3]1,038	538

[1]Estimate was 500–700-lb/acre increase under "favorable" conditions which suggests average or above average precipitation. Pretreatment production was 106 lb/acre at Oak Creek.

[2]The 1,415-lb per acre estimate represents a typical estimate of production for the Oak Creek area in favorable years, and the 780 lb/acre represents an estimate of production for below-average soils in the Oak Creek area in favorable years (Stoneman and others 1978).

[3]Average for estimates of favorable and unfavorable years for typical soil conditions.

In addition, the production data from Clay Springs were further adjusted to account for less productive eolian soils to place these values on a par with the other three study areas (table 7). The adjusted production data were assumed to more accurately represent changes over time under conditions of average precipitation and average soil conditions. The data suggest a peaking of production 6 to 8 years after seeding at about 550 lb per acre and a gradual decline to approximately 450 lb per acre in older seedings (fig. 3). Using 500 lb as the best estimate of average long-term production potential, the study areas at Oak Creek still appeared to be at least one productivity class less than assumed in the RPA scenario for an "average" pinyon-juniper site (table 9). The adjusted average value for the swale bottom topographic position (628 lb per acre) also fell short of the "average" expected production (850 lb per acre).

DISCUSSION

The reasons plant production did not meet assumed production levels are not known. A major problem occurs in fitting a specific area into a nonspecific array. Without clear identifiers the proper location within an array, such as that in table 3, may involve a bit of guesswork. Some elements of the environment such as precipitation and soils provide clues, but no specific guides are available. When a viable classification of the pinyon-juniper type is developed, the proper positioning of a particular area within such an array will be more likely. The best approach to evaluate or test an array of production coefficients for a wide-ranging vegetation zone would be to draw unbiased samples from across the vegetation zone and determine the statistical distribution of measured outputs. This would alleviate the need to identify the exact "pigeon-hole" into which an individual location fits.

A second question is whether the production levels were assumed to represent grazed or nongrazed situations. A review of recent literature suggests that, after tree removal, *grazed* pinyon-juniper areas rarely exceed 800 lb per acre except in localized situations. Conversely, after tree removal *ungrazed* pinyon-juniper areas often exceed 1,200 lb per acre (Clary 1987). Presumably, the grazed situation should apply to the RPA assumptions because the key issue was a question of AUM's of grazing capacity. However, this problem was not recognized in the RPA scenario nor in the local assumptions.

Another possible problem concerns the production trends of seeded stands. Stands of good initial density, which are often established when drilling or other intensive revegetation techniques are used, typically peak in production after 2 to 3 years (White 1985). These stands then decline through at least the sixth year to about 50 percent of their peak value (fig. 5). If production sampling occurs during the peak production period, the values obtained are highly biased estimates of long-term average production. A different pattern occurs when the seeded stand is sparse or when no seeding is done and the native vegetation is allowed to recover naturally. A thickening of the stand and an increase in production may occur for some years, particularly if sodformers are part of the composition. In their Southwestern study, Arnold and others (1964) found approximately 10 years were required to achieve maximum production of herbage after juniper removal (fig. 6). A similar pattern undoubtedly occurs in

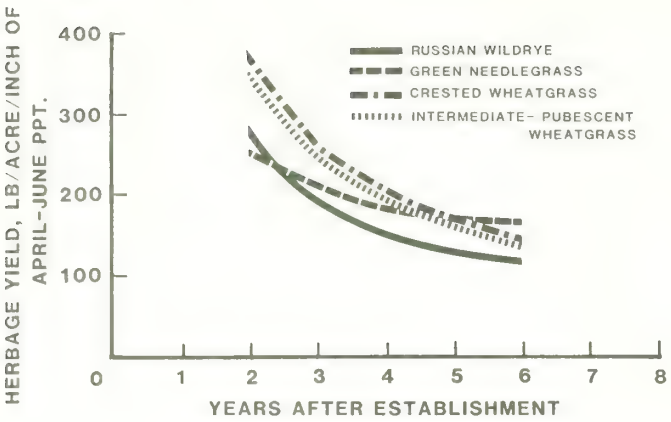

Figure 5—Effects of stand age on herbage yield in the Northern Great Plains per inch of April through June precipitation (after White 1985).

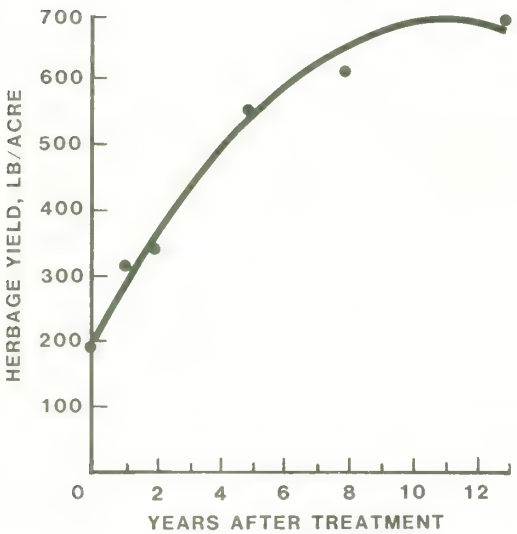

Figure 6—Herbage yields by number of growing seasons after control of juniper and pinyon (after Arnold and others 1964).

many Intermountain chaining and seeding efforts wherein the initial stands are often thin in comparison to stands obtained by more intensive seeding techniques. In such instances, a continued thickening of the stand often results in continued gain in production for several years because the total rooting zone was not initially occupied. Depending upon initial conditions and plant composition, we might expect a difference of up to 8 years among stands as to when their peak production is achieved.

In other reported pinyon-juniper treatments from Utah, 717 lb per acre were produced 7 years after a cabling and seeding treatment in a precipitation year that should have produced yields 132 percent of normal (Christensen and others 1966). Thus, yields to be expected in a median precipitation year (Sneva and Britton 1983) were approximately 543 lb per acre. About 700 lb of total herbage increase per acre was produced 5 years after chaining in 59 projects in southern Utah (Phillips 1977). Many of these projects could have been near peak production if they followed the trend illustrated in figure 3. The data of Payne and Busby (1980) showed an average of only 379 lb per acre of grasses with few forbs were produced on 18 chainings 6 to 25 years old on National Forests in Utah. Although production of shrubs was not determined, the rate of grass production was about the same as occurred on the most recent treatment areas at Oak Creek—Church Hills and Clay Springs (~350 to 400 lb per acre). The average annual precipitation for these sites was approximately 14 inches or about the estimated long-term mean for the study areas at Oak Creek.

CONCLUSIONS

Direct comparisons of different treatment areas are difficult because many important factors such as weather, soils, grazing history, and plant composition are often not recorded. However, general patterns in the data provide some guidance. Results from the Oak Creek Mountain Range Evaluation Area, examined from several viewpoints, and other published results support a conclusion that RPA assumptions and soil report estimates of herbage and shrub production potential were overly optimistic for average long-term grazed conditions in central Utah pinyon-juniper. The swale bottom topographic position was the only situation with sufficient productivity to approach expectations of the RPA coefficient matrix. The estimate of overall forage production provided by the Forest Service environmental statement was the most accurate.

Factors that cause difficulties in making accurate site predictions from assessment matrices include: (1) few guides for positioning a specific site within the assessment matrix; (2) lack of information on grazed or ungrazed situation of original data sources; and (3) lack of information concerning the age and original seeding success of seeded stands.

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RPA production assumptions, an environmental statement, and a soils report are available as bases for management planning. To test these assumptions a study was developed using four different-aged areas of pinyon-juniper removal and forage plant seeding. Data were collected over an 8-year period to provide ground data against which to test assumptions.

KEYWORDS: evaluation area, chaining, seeding, topographic position

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Forage Quality in Burned and Unburned Aspen Communities

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RESEARCH SUMMARY

We assessed the effects of fire on the quality of herbaceous and browse forage for elk (*Cervus elaphus*) and domestic sheep in the aspen (*Populus tremuloides*) forest type. Selected forage species were sampled on burned and adjacent unburned areas during the summers of the first and second years after autumn prescribed burning of three sites in southeastern Idaho. These samples were analyzed for in vitro dry matter digestibility (IVDMD), crude protein, calcium, and phosphorus. This aspen type has a highly nutritious understory irrespective of burning. We found additional improvement in forage quality as a result of prescribed burning. In the middle of the first summer, aspen on the burned areas had higher crude protein and phosphorus contents, higher elk IVDMD, lower calcium contents, and lower calcium/phosphorus ratios than aspen had on the unburned areas. A month later, only crude protein levels of aspen remained higher on the burns. All of the shrubs analyzed in the first summer had higher crude protein levels on the burned areas. A year later, none of the shrubs or forbs on the burns had better forage quality than those under nearby unburned aspen. Pinegrass (*Calamagrostis rubescens*) on the burned areas in the second summer had more robust growth but lower IVDMD and crude protein values, likely due to more extensive flowering and seed production, than did pinegrass on unburned areas. Prescribed burning on these sites changed species composition from dense shrub motts to more palatable and nutritious forbs than were found on the unburned areas.

Cover illustration: Aspen regeneration amidst lush grass and forb production 2 years after prescribed fire in the Bridger-Teton National Forest, WY.

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INTRODUCTION

There are more than 7 million acres (3 million hectares) of aspen (*Populus tremuloides* Michx.) in the West. Very likely fire has played an important role in maintaining most of this aspen. On the majority of sites, aspen is even-aged and is seral to conifers. A stand-killing fire at any time prior to the disappearance of aspen from a conifer stand often will result in a stand of vigorous aspen suckers (Jones and DeByle 1985). Many decades of fire control in the West have resulted in mature to old aspen stands on most sites (Shepperd 1981). Wildfire in the aspen forest today is an unusual event (DeByle and others 1987).

Silviculturists and wildlife biologists alike generally feel that a predominance of mature to old stands of aspen is not desirable for either the forest or wildlife. Hence, with increasing frequency in the West, land managers are taking steps to rejuvenate aspen on public lands. These steps include the use of prescribed fire to kill conifers that are taking over aspen sites and to kill the existent aspen trees for the purpose of stimulating growth of vigorous stands of young even-aged aspen root suckers (fig. 1). A multiaged mosaic of even-aged aspen stands eventually should be found in western forests.

Figure 1—A helitorch being used to burn mature and decadent aspen in the Bridger-Teton National Forest.

Figure 2—Three years after fire killed the aspen overstory, a dense stand of grasses, forbs, and aspen suckers occupies this Manning Basin site.

The understory in aspen usually is lush and contains many species palatable to both livestock and big game. Fire may increase at least the herbaceous component of this understory (Bartos and Mueggler 1981) (fig. 2). The attraction of burned areas to foraging ungulates, particularly big game, has led to frequent speculation that the forage on these burns is more nutritious than on adjacent unburned areas. This has been tested and found to be true for many vegetation types. The fiber content is often lower and the protein and phosphorus contents higher in the regrowth during the first couple years following fire (Blank 1984). However, no test of this hypothesis for the western aspen-shrub community could be found in the literature. Therefore, we conducted an experiment with the following objectives:

1. To determine nitrogen, calcium, and phosphorus concentrations in aspen sprouts and selected species of grasses, forbs, and shrubs common to both burned and unburned aspen communities.
2. To compare in vitro digestibilities for elk and for domestic sheep of these plant species from both treatments.

MATERIALS AND METHODS

We selected three sites in the Caribou National Forest about 20 miles (30 km) west of Afton, WY. All three had been prescribed burned in the autumn of 1981. Burn severity ranged from high (Manning Basin site) to moderately low (Snowdrift I and II sites). These sites were in the *Populus tremuloides/Amelanchier alnifolia—Symphoricarpos oreophilus* plant community. These characteristic tall shrubs grow within an herbaceous understory dominated by *Calamagrostis, Elymus, Lupinus,* or *Geranium* (Mueggler and Campbell 1982).

Plant samples were collected during the summers of 1982 and 1983 from the burned and adjacent unburned areas on each site. For the most part, we gathered only those species that made up the majority of forage and were common to both the burned and unburned areas. Each sample of a species consisted of material from 25 to 30 randomly selected plants. Woody plants were sampled by stripping the leaves and terminal segments of the current year's twigs. The entire aboveground portion of grasses and forbs was collected. Samples were immediately weighed to determine moisture content. They were put on ice in the field and frozen later that day. Prior to analyses, they were ovendried at 50 °C, weighed again, and ground to pass through a 1-mm screen.

The Tilley and Terry (1963) technique as modified by Moore (1970) was used to determine in vitro dry matter digestibility (IVDMD). Rumen fluids from elk and domestic sheep, both maintained on alfalfa hay and pellets, were used for the IVDMD analysis.

The concentrations of nitrogen, calcium, phosphorus, dry matter, and ash were determined for each sample. The macro-Kjeldahl technique (A.O.A.C. 1965) was used to determine nitrogen. Plant samples for determination of calcium and phosphorus were ashed at 500 °C, put into solution in an acid medium, and filtered. Phosphorus was determined with a spectrophotometer using the ammonium molybdate-ANSA method (Harris 1970), and calcium was determined using the EDTA titration technique (Allen and others 1974).

We subjected these data to an analysis of variance. There were three replications (sites), two treatments (burned and unburned), nine plant species, and several collection dates.

The major comparison for the first postburn year (1982) consisted of one date and five species; the major comparison for the second postburn year (1983) consisted of three dates and nine species. The five species analyzed from August 22, 1982, were: aspen, serviceberry (*Amelanchier alnifolia*), snowbrush (*Ceanothus velutinus*), chokecherry (*Prunus virginiana*), and pinegrass (*Calamagrostis rubescens*). Another test for the first field season used two dates (August 2 and 22) but only two species, aspen and pinegrass.

In 1983, the three dates were July 15, August 15, and September 15. The nine species included the same five species as in 1982 plus blue wildrye (*Elymus glaucus*), sticky geranium (*Geranium viscossissimum*), blue lupine (*Lupinus argenteus*), and heart-leaf arnica (*Arnica cordifolia*).

For a year-to-year comparison, the five species from August 22, 1982, were matched with the same species from August 15, 1983. We also made a comparison using only aspen and pinegrass for both August 2 and 22, 1982; and July 15 and August 15, 1983.

Additional analyses using the least squares estimator, or in case of no overall statistical significance, the Sheffe LSD test, were used to test for differences between species means (Neter and Wasserman 1974).

All differences discussed in this paper are significant at least at the 0.05 percent probability level.

RESULTS AND DISCUSSION

Plant phenological stages were observed to be similar on both burned and unburned areas. Forbs bloomed throughout the season. Thus, several phenological stages of forbs overlapped within and between the burned and unburned areas. Pinegrass produced many culms and flowers in the burned areas but only a few in the unburned areas. Shrubs on the burned areas neither flowered nor set seed during either summer. So, dates instead of phenological stages are used for comparisons.

Irrespective of burning, changes in forage quality occurred as the season progressed. In the second year, for example, the earliest sampling yielded the highest quality (table 1). Also, over the entire season, there were marked differences among species (table 2). Forbs had higher digestibilities than shrubs or grasses.

Fire improved forage quality during the first postburn growing season (1982). Aspen on the burned areas on August 2, 1982, had a better calcium/phosphorus ratio, higher elk digestibility, higher crude protein and phosphorus levels, and a lower calcium content than on the unburned sites. However, 3 weeks later only phosphorus and crude protein levels were greater on burned sites (table 3). At that time, all shrubs on the burned areas had higher crude protein levels. Two (serviceberry and chokecherry) had lower phosphorus levels, and chokecherry had a lower calcium level (table 4). In the second growing season (1983), there were no improvements in quality of either shrubs or forbs that could be attributed to burning.

Some of the changes in quality of shrubs could be due to changes in growth form on the burns. In early August of the first year, most shrubs on the burned areas were less than 1 ft (30 cm) tall and had fewer stems and larger leaves than on unburned areas. By late August, secondary branching had appeared and the plants were up to 2 ft (60 cm) tall. In the second summer, these shrubs were 3 to 5 ft (100 to 150 cm) tall, with more branches and smaller leaves. Thus, shrubs in early August of the first postburn year had lower stem-to-leaf ratios than they did later in that summer or in the second year.

Higher levels of phosphorus in plants from burned areas were found only in aspen and only on August 2 of the first year. All of the other samples from the burns had either lower levels of phosphorus or did not differ from the unburned sites (tables 3, 4, and 5). Our findings are similar to those of others (Halls and others 1952; Meenely and Schemnitz 1981; Swank 1958).

Table 1—IVDMD and nutrient concentrations of all forage species combined on three dates in 1983

Date	IVDMD		Protein	Calcium	Phosphorus
	Sheep	Elk			
	Percent				
July 15	[1]65.9	60.2	[1]16.3	[1]1.28	[1]0.33
August 15	58.6	61.6	12.5	1.57	.27
September 15	57.5	60.1	10.9	1.70	.29

[1]Significantly (p=0.001) different from values on other two dates.

Table 2—Average digestibility and nutrient concentration of each species in the second postburn summer; treatments, dates, and sites are pooled

Species	IVDMD		Protein	Calcium	Phosphorus
	Sheep	Elk			
Shrubs			*Percent*		
Populus tremuloides	[1]53.8a	55.5ab	15.4cd	1.45	0.26abc
Ceanothus velutinus	57.0b	57.8b	14.2bc	1.28	.21a
Amelanchier alnifolia	56.7ab	59.0b	14.6c	1.58	.43d
Prunus virginiana	55.2ab	58.7b	15.0cd	1.92	.36cd
Grasses					
Calamagrostis rubescens	55.6ab	52.5a	10.5a	0.81	.21a
Elymus glaucus	56.6ab	55.5ab	13.1b	1.11	22a
Forbs					
Geranium viscosissimum	70.4cd	69.0c	13.1b	1.98	.39d
Lupinus argenteus	68.9c	67.7c	16.0d	1.55	.24ab
Arnica cordifolia	72.0d	69.9c	9.7a	1.99	.35bcd

[1]Within each column, the means not followed by a common letter are statistically different (p=0.05).

Table 3—Sheep and elk IVDMD, and concentrations of crude protein, phosphorus, and calcium of aspen and pinegrass that were collected on two dates (August 2 and 22, 1982)

Species	Date	Treatment	IVDMD		Protein	Phosphorus	Calcium
			Sheep	Elk			
					Percent		
Populus tremuloides	August 2	Burned	[1]43.5a	61.8d	21.7d	0.39d	1.47b
		Unburned	50.3a	51.8abc	15.8c	24ab	1.78c
	August 22	Burned	57.9a	48.7ab	19.2d	.32cd	1.88c
		Unburned	53.5a	48.3a	14.2bc	.27b	1.86c
Calamagrostis rubescens	August 2	Burned	53.7a	54.7abc	13.5abc	23ab	54a
		Unburned	52.7a	48.9ab	10.3a	23ab	79a
	August 22	Burned	54.6a	57.1cd	11.5ab	19a	.54a
		Unburned	56.8a	55.9bcd	10.5a	20ab	.74a

[1]Means in columns not followed by a common letter are statistically different (p=0.05).

Table 4—Sheep and elk IVDMD, and concentrations of crude protein, phosphorus, and calcium of five forages collected on August 22, 1982

Species	Treatment	IVDMD		Protein	Phosphorus	Calcium
		Sheep	Elk			
		Percent				
Populus tremuloides	Burned	[1]54.7ab	47.8ab	19.1e	0.32cd	1.66c
	Unburned	49.4ab	47.5ab	14.1bc	28bc	1.87cd
Ceanothus velutinus	Burned	49.1ab	47.4ab	18.2e	23abc	.93ab
	Unburned	48.7ab	47.5ab	14.4c	.14a	1.20b
Amelanchier alnifolia	Burned	50.6ab	50.4ab	18.1e	39d	1.75cd
	Unburned	48.2ab	44.2a	15.0cd	.57e	2.07de
Prunus virginiana	Burned	45.9ab	47.0ab	17.7e	.29bcd	1.64c
	Unburned	44.2a	45.2a	14.9cd	.60e	2.37e
Calamagrostis rubescens	Burned	51.6ab	52.9ab	11.4ab	19ab	.55a
	Unburned	56.5b	57.6b	10.8a	.20ab	.73a

[1]Values within columns not followed by a common letter are statistically different (p=0.05).

Table 5—IVDMD and nutrient concentrations in five forage species collected on August 22, 1982, and August 15, 1983, sites and treatments are pooled

Species	Treatment	IVDMD				Crude protein		Phosphorus		Calcium	
		Sheep		Elk							
		First summer	Second summer	First summer	Second summer	First summer	Second summer	First summer	Second summer	First summer	Second summer
		Percent									
Populus tremuloides	Burned	[1]54.7de	52.1cde	47.8abc	56.9ef	19.1h	14.1cdef	0.32bcde	0.17a	1.66	1.18
	Unburned	49.4bcd	49.3bcd	47.5abc	55.2de	14.1def	14.1def	28abcd	25abcd	1.87	1.67
Ceanothus velutinus	Burned	49.1bcd	54.1de	47.4abc	61.9f	18.2gh	14.5def	23abc	20ab	.93	1.34
	Unburned	48.7abc	53.0cde	47.5abc	60.9f	14.4def	15.0ef	14a	.21ab	1.20	1.72
Amelanchier alnifolia	Burned	50.6cd	52.9cde	50.4bcd	57.0ef	18.1gh	15.6efg	.39de	39de	1.75	1.36
	Unburned	48.2abc	52.2cde	44.2a	56.6ef	15.0ef	13.8cde	57fg	45fe	2.07	1.42
Prunus virginiana	Burned	45.9ab	55.1ef	47.0abc	59.6f	17.7gh	14.6def	29bcd	21a	1.64	1.56
	Unburned	44.2a	54.5de	45.2ab	58.7d	14.9ef	15.6efg	60g	.37cde	2.37	1.90
Calamagrostis rubescens	Burned	51.6cd	49.6bcd	52.9de	46.7ab	11.4bc	6.8a	.19ab	20ab	.55	.89
	Unburned	56.5ef	59.1f	57.6ef	56.2ef	10.4b	12.2bcd	.20a	21ab	73	1.27

[1]For each pair of columns (first and second summers), the means not followed by a common letter are statistically different (p=0.05).

Figure 3—One year after a severe stand-killing fire in the aspen there is almost a complete coverage of globemallow and pinegrass on this Manning Basin site.

The calcium concentration of plants was generally lower on burned areas than it was on nonburned areas. Lay (1957) reported similar findings. Lower calcium contents produce lower calcium/phosphorus ratios on these burned areas. The possibility of interference with phosphorus metabolism in the animal is reduced with low calcium/phosphorus ratios. Burning, at least in the first postburn year, improved calcium/phosphorus ratios by lowering them. Even then, with the exception of grass, all of our plant samples had much higher ratios than optimal for ruminants. Ratios of 1:2 to 2:1 are excellent, 2:1 to 3:1 are good, 3:1 to 5:1 are fair, and those larger than 5:1 are poor (Urness 1973). However, plants poor in phosphorus may be good sources of protein, energy, or other nutrients.

Pinegrass in the first postburn year was similar on both burned and unburned areas (tables 3 and 4). (Different August 22 values in tables 3 and 4 are due to different subsamples and runs on aspen and pinegrass; the data are correct.) By the next year, pinegrass on burned areas was significantly lower in digestibility and crude protein than on unburned areas (table 5).

Vegetative reproduction of perennial species usually occurs rapidly and vigorously after burning (Hadley 1970; Old 1969; Vogl 1965; Wright 1969). Shoots of herbaceous species produced after fire often are stiffer and more erect than on unburned sites (O'Connor and Powell 1963). Increased numbers of grass and forb flowers are stimulated by burning (Curtis and Partch 1950; Ehrenreich and Ackman 1963; Lemon 1949, 1968; Lloyd 1972), including pinegrass (Crane and others 1983; Weaver 1974). On our sites, pinegrass on the severely burned areas not only produced more biomass, but uniformly flowered and produced a seed crop as well (fig. 3).This flowering and seed production of pinegrass likely caused the decrease in its quality on the burned areas (Chapin and Van Cleve 1978; Van Soest 1982).

Flowering in forbs increased, too; but it is not usually associated with large changes in nutritive value, despite leaf loss through senescence (Van Soest 1982). Thus, the forbs had higher forage quality at the end of the season than did the grasses, even though their phenology was similar.

Our study showed that burning causes changes in the digestibility and nutrient content of selected species growing in common on burned and unburned sites. However, relatively much larger changes in forage species composition and structure occurred on these sites after fire (figs. 2 and 3). These, no doubt, were more important to ruminants than our documented changes in nutrient contents or digestibility (Canon and others 1987).

Fire, followed by an excellent growing season, stimulated a large increase in herbaceous biomass production. On inventoried plots in Manning Basin, the forbs, from a preburn base of 85 lb/acre (95 kg/ha), increased almost eightfold in the first postburn growing season and, in the second, about fifteenfold, to 1,254 lb/acre (1,405 kg/ha). Grass production increased from 280 lb/acre (315 kg/ha) to 646 lb/acre (724 kg/ha) in the first year and to 516 lb/acre (578 kg/ha) in the second. The shrub component was reduced as dramatically as the forb component increased. (Brown and DeByle, in preparation, and unpublished data on file at the Intermountain Fire Sciences Laboratory, Forest Service, Missoula, MT.)

The forb species that dominated the postburn vegetation were not those sampled extensively in this study. A globemallow (*Iliamna rivularis*) that was not found prior to burning was the most abundant forb on these sites afterwards. Fireweed (*Epilobium angustifolium*) was also common on the burned areas but was nonexistent on the control areas. Both of these forbs were sampled in the second year. They had digestibilities over 80 percent throughout the second summer. Crude protein levels were also high, averaging 20 percent for fireweed and 18 percent for mallow. Wherever cattle and sheep grazed on the burned sites, these two forbs were highly preferred, often grazed to ground level. This was especially true in the first postburn year when these plants were quite succulent. Thus, burning introduced highly preferred and nutritious forages that otherwise would not have occurred on these sites. Free-ranging tame elk preferred the burned sites in the second and third summers after treatment. The composition and quality of their chosen diets are reported by Canon and others (1987).

CONCLUSIONS

The benefits of these prescribed fires to ruminants, both wild and domestic, are substantial during the summer and autumn of the first several postburn years. Our burns provided a more nutritious forage resource than before, when shrubs dominated these sites. Forage also became more accessible because dense shrub motts were reduced. The height of forage, after burning, was totally within the grazing zone, in contrast to unburned sites dominated by shrubs, where much of the biomass often is above the reach of grazing ungulates. Thus, on these burned areas, animals could obtain a high-quality diet with relative ease (Canon and others 1987).

Generally, with or without burning, the nutritive quality of aspen understory is high (Collins and Urness 1983, Canon and others 1987). The quality of our selected species improved only in the first postburn year. Wood (1988) found similar transient improvement in pine understory in South Carolina. In our study, we found that few species dropped below 50 percent digestibility even in late September. The shrubs averaged about 14 percent crude protein for all dates. The grasses and some of the forbs decreased to about 7 percent crude protein in late September, but still within the maintenance requirements for at least adult mule deer (Dietz 1965). All of the plants were still green and growing in September.

Prescribed burning increased forage quality of species that were common to both burned and adjacent unburned sites, but only briefly. By the second postburn year, the quality of most forages did not differ significantly between treatments. Despite the inconsistent and transient improvement in quality of individual forage species, prescribed burning remains a useful tool to alter forage species composition and forage availability in the aspen-tall shrub community.

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Selected forage species were sampled during the first and second summers after autumn prescribed burning of three sites in southeastern Idaho. They were analyzed for in vitro dry matter digestibility, protein, calcium, and phosphorus. This aspen type has a highly nutritious understory. Burning further improved the quality of the selected species only during the first postburn summer. Burning, however, changed species composition from shrubs to an abundance of palatable and nutritious forbs.

KEYWORDS: fire effects, crude protein, calcium, phosphorus, dry matter digestibility, Idaho, wildlife habitat, prescribed fire

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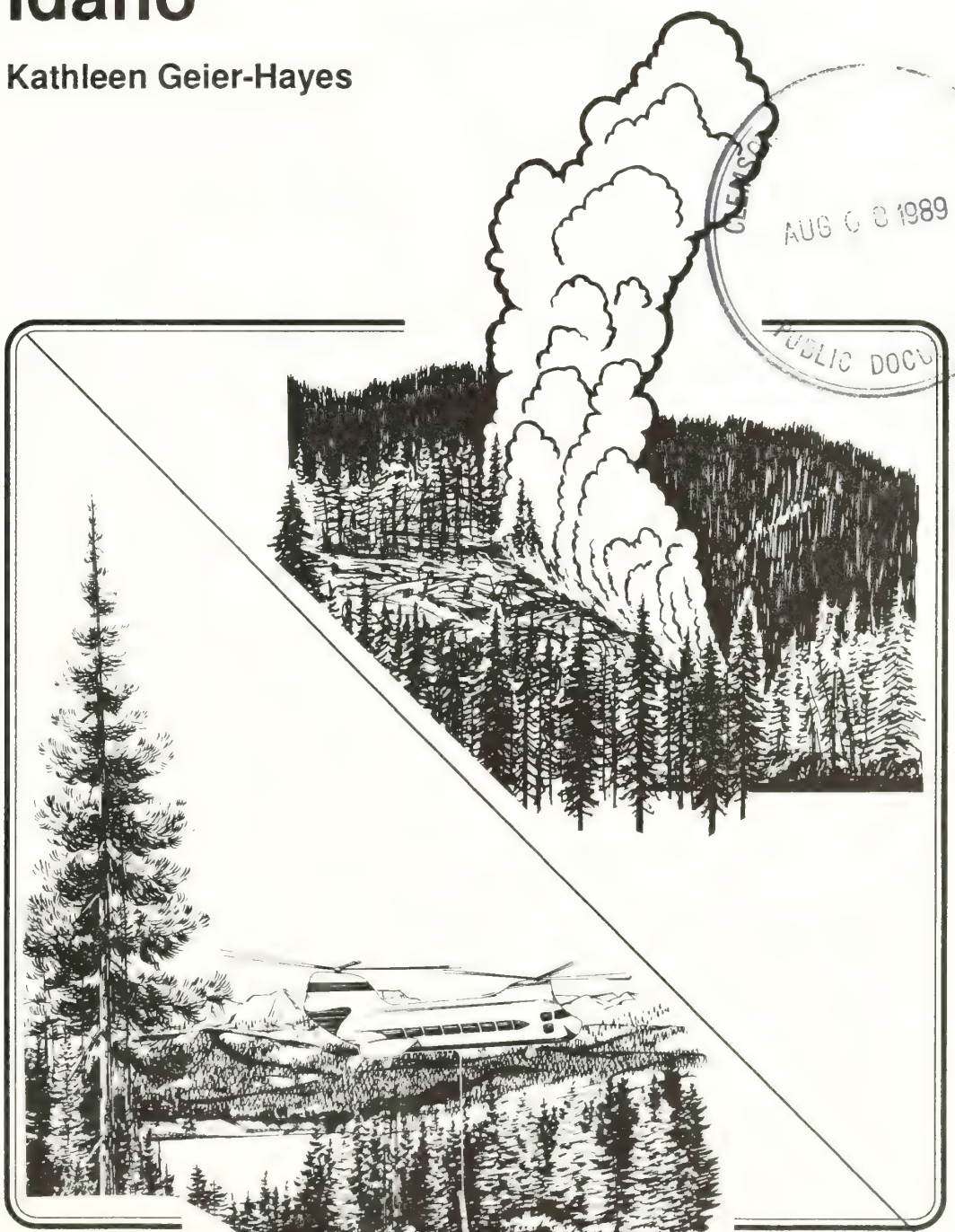
Vegetation Response to Helicopter Logging and Broadcast Burning in Douglas-fir Habitat Types at Silver Creek, Central Idaho

Kathleen Geier-Hayes



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RESEARCH SUMMARY

Vegetal response of shrubs and herbs (forbs and graminoids) was measured on 12 plots in the *Pseudotsuga menziesii/Spiraea betulifolia* and *Pseudotsuga menziesii/ Physocarpus malvaceus* habitat types (h.t.) at the Silver Creek Study Area in central Idaho. The plots were located throughout three designated cutting units and were surveyed prior to harvesting in summer 1976. Shrub frequency, cover, and height were measured as well as herb cover and frequency. The cutting units were logged and helicopter yarded during fall 1976. One cutting unit was broadcast burned in December 1976 while the other two were broadcast burned in February 1977. Based on the Ryan-Noste fire severity rating (Ryan and Noste 1985), the burning in December was a 3-M while the burning in February was a 2-M. Plots were remeasured 1, 2, 5, and 10 years after the disturbance. Comparisons of unburned and burned plots in the 2-M burned cutting units showed little difference in the recovery of most major shrub and herb species. Vegetal composition after 10 years was essentially the same as the original with only a few exceptions. One shrub, *Symphoricarpos albus*, increased throughout the cutting area, though the increases were the same on unburned and burned plots. Herb composition changed slightly in that annuals and short-lived perennials increased on most of the cutting area. Two forbs, *Arnica cordifolia* and *Lathyrus nevadensis*, decreased throughout the cutting unit as a result of the treatment.

Vegetation on the 3-M burned plots was altered from the original. Unburned plots in the 3-M burned cutting unit were similar to both unburned and burned plots in the 2-M burned cutting unit. However, vegetation on 3-M burned plots was dominated by *Ceanothus velutinus* after 10 years even though little was present in the predisturbance community. Two other species, *Physocarpus malvaceus* and *Carex geyeri*, appeared to have been retarded by the more severe burning.

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Vegetation Response to Helicopter Logging and Broadcast Burning in Douglas-fir Habitat Types at Silver Creek, Central Idaho

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INTRODUCTION

Helicopters are often used to remove logs from steep harvest areas with unstable soils. This harvesting method reduces the need for movement of machinery and logs over the site, thereby decreasing the amount of site and soil disturbance. Consequently, helicopter logging has little physical impact on the soil and understory vegetation. Dyrness (1972) found that only 20 percent of the soil surface in a balloon-logged clearcut was "slightly" or "deeply" disturbed and that bare mineral soil was exposed over only 6 percent of the area. However, while minimal soil disturbance reduces erosional hazards (Megahan 1974) silviculturists are concerned that the lack of soil disturbance will retard conifer regeneration because bare mineral soil is a preferred seedbed for many conifer species. Large amounts of residual debris can also inhibit conifer regeneration and increase the fire hazard (Bjornsen and Mustian undated). Silviculturists are faced with the dilemma of how to prepare a site for regeneration and to reduce slash, without negating the use of a low-impact yarding system. Machine scarification, though often used in central Idaho, is not compatible with helicopter logging. However, prescribed burning is an alternative. Little is known, though, about the effects of broadcast burning on the dry forest environments of central Idaho. Lyon (1971) conducted a study of vegetal development following broadcast burning in central Idaho on a moist forest habitat and found that most species on the site survived the burning, though the composition of the vegetation was altered. Many researchers (Crane and others 1983; Dyrness 1973; Lyon and Stickney 1976) concluded that the postburn communities are greatly influenced by the preburn community because many species are capable of resprouting. Lyon and Stickney (1976) found that most species that survive burning will reestablish within the first year of the disturbance. Total cover of vegetation often exceeds preburn levels within 8 to 10 years following the burning (Dyrness 1973), though the composition is often altered. Results from Lyon's (1971) study were similar; total understory cover was approaching the preburn levels and would have exceeded it except for the slow recovery of one major species. However, Merrill and others (1982) caution that effects of burning on vegetation in drier environments may be different than the effects in more moist environments. Most of the vegetation response studies have been conducted in forest environments that are much more moist than many of the forest environments in central Idaho, and the response may not be the same.

STUDY AREA

The study is in west-central Idaho 50 miles north of Boise, ID, in the Silver Creek Study Area on Control Creek, a tributary of Silver Creek (fig. 1). Control Creek drains 404 acres of Idaho batholith, an area of steep slopes overlain with highly erodible granitic rock (Clayton and Kennedy 1985). The soils are coarse textured, lack cohesion, and are very erodible following disturbance. Slope angles within the study area range from 18 to 55 percent. Elevation ranges from 4,650 to 5,850 ft. The mean annual maximum temperature from 1976 to 1985 was 52 °F while the mean annual low temperature was 30 °F. The average annual precipitation over the 10 years was 36 inches, most of which fell from October to March. Only a small amount (average 1.4 inches) fell during June, July and August. Two abnormally dry periods occurred during this 10 years. The first was from September 1976 through April 1977 when precipitation levels were only 33 percent of normal (unpublished data on file at the Forestry Sciences Laboratory, Boise, ID). The second dry period occurred from December 1985 through August 1986 when precipitation levels were only 56 percent of normal.

Two habitat types (h.t.) as described by Steele and others (1981) dominate in the Control Creek drainage: *Pseudotsuga menziesii / Spiraea betulifolia* h.t., *Pinus ponderosa* phase and *Pseudotsuga menziesii / Physocarpus malvaceus* h.t., *Pinus ponderosa* phase. The *Pseudotsuga menziesii / Spiraea betulifolia* h.t. occurs in drier areas of the Douglas-fir zone than does the *Pseudotsuga menziesii / Physocarpus malvaceus* h.t. Climax understory vegetation in the *Pseudotsuga menziesii / Spiraea betulifolia*

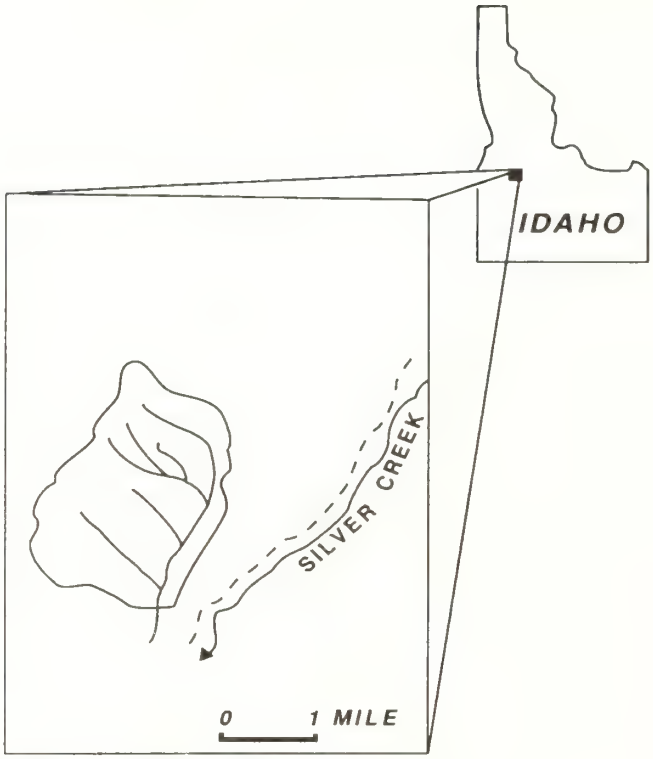

Figure 1—Location of Silver Creek Study Area.

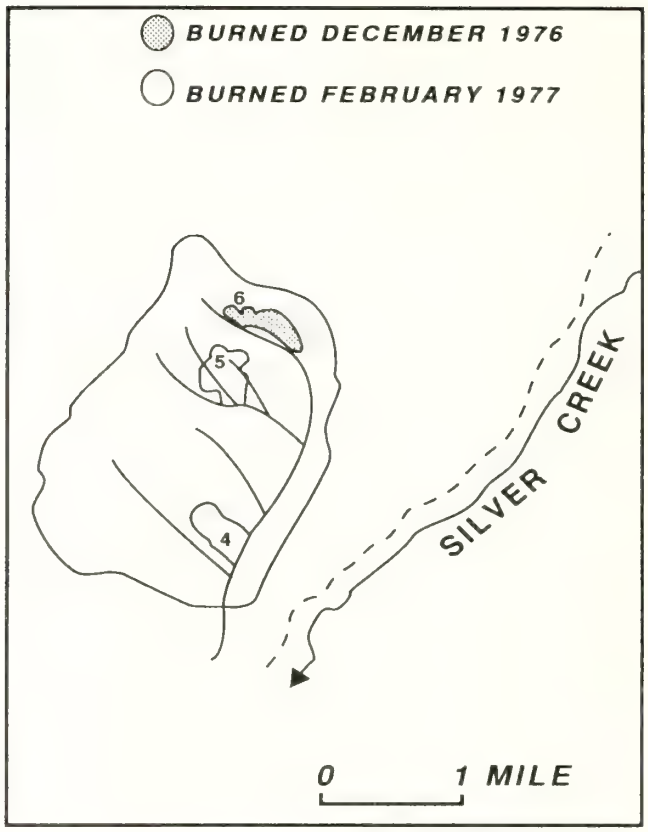

Figure 2—Location of cutting units within the Silver Creek Study Area.

h.t. normally consists of the low shrub *Spiraea betulifolia* with a layer of graminoids including *Calamagrostis rubescens* or *Carex geyeri* beneath the *Spiraea*. *Amelanchier alnifolia*, and *Salix scouleriana* are also common. In the *Pseudotsuga menziesii / Physocarpus malvaceus* h.t., the shrub *Physocarpus malvaceus* usually dominates the site. *Amelanchier alnifolia*, *Spiraea betulifolia*, and *Berberis repens* often occur. The *Pseudotsuga menziesii / Physocarpus malvaceus* h.t., which represents a warm, moist environment in the *Pseudotsuga menziesii* zone, is found most commonly on north aspects in central Idaho. However, it was found in Control Creek on south-facing slopes. In this case, it represents the dry extreme of the habitat type and the vegetation was similar to the vegetation in the *Pseudotsuga menziesii / Spiraea betulifolia* h.t., except for the presence of the *Physocarpus malvaceus*.

METHODS

Overmature stands of *Pinus ponderosa* and *Pseudotsuga menziesii* were logged and helicopter yarded during September through November 1976. Three cutting units designated 4, 5, and 6 were clearcut of all trees greater than 10 inches diameter breast high (d.b.h.). All smaller trees were left standing. Unit 4 is at the lower end of the drainage, unit 5 is halfway up the drainage, and unit 6 is near the top of the drainage (fig. 2). Unit 6 was accidentally burned in December 1976 while units 4 and 5 were prescribed burned in February 1977. When unit 6 burned, only 19 percent of the normal precipitation had fallen since September 1976, and weather conditions were unusually dry and warm. Though only 23 percent of the normal precipitation had fallen when units 4 and 5 burned, some snow was present on the ground. Using the Ryan and Noste (1985) fire severity rating, the burning resulted in a rating of 2-M for units 4 and 5 and 3-M for unit 6. Basal area for cutting units 4 and 5 was reduced 93 percent to 13 ft^2 per acre following the harvesting and burning (table 1). On unit 6, basal area was reduced 94 percent to 12 ft^2 per acre. The harvesting and burning treatment has resulted in an 80 times greater erosion rate for a 10-year period following the treatment compared to an undisturbed stand (Megahan 1988). The accelerated erosion has been attributed to the bare soil exposed by the burning rather than the helicopter yarding.

Sampling Procedure

Prior to the logging, in the summer of 1976, 12 permanent macroplots were located throughout the units with four plots (two of each habitat type) in each unit. Plots were situated on south or southwest aspects to evaluate

Table 1—Trees per acre by 4-inch diameter breast high (d.b.h.) classes and basal area per acre for *Pinus ponderosa* and *Pseudotsuga menziesii* in cutting units 4/5 and 6

Unit and species	Trees per acre											Basal area per acre
	<4.5 ft	0-4	5-8	9-12	13-16	17-20	21-24	25-28	29-32	33-36	37-40	
CUTTING UNIT 4/5												
Pinus ponderosa												
1976	1	167	15	20	9	9	11	4	3	1	1	126
1977	1	30	4	11								8
1978	3	24	4	11								8
1981	7	20	8	8								7
1986	8	21	7	7	1							8
Pseudotsuga menziesii												
1976	0	102	8	3	3	5	11	0	4	0	0	69
1977	1	19	11	3								5
1978	4	16	11	3								4
1981	13	16	9	3								4
1986	3	22	9	4								5
CUTTING UNIT 6												
Pinus ponderosa												
1976	0	57	11	11	0	5	3	11	5	0	0	96
1977	0	8	8	5								5
1978	0	8	5	5								5
1981	0	3	3	8								6
1986	0	3	3	3	5							8
Pseudotsuga menziesii												
1976	0	57	22	16	11	16	5	5	0	0	0	94
1977	0	30	19	3								7
1978	0	19	11	3								5
1981	46	13	11	3								4
1986	0	11	13	5								7

a "worst case" scenario for the treatment. Macroplots were 49 by 82 ft and were orientated with their long axis paralleling the contour (fig. 3). At intervals of 16 ft along the axis, perpendicular to the contour, two transects of 25 contiguous plots, 3.3 by 3.3 ft (miniplots), were located. Within each miniplot, an 8- by 20-inch plot (microplot) was established.

Microplot

Herbaceus vegetation (forbs and graminoids) was sampled in the microplots for frequency of rooted occurrence (rooted presence or absence) and canopy coverage (without regard to rooting). Precision for frequency resulted in a minimum interval of 2 percent. Canopy coverage was visually estimated in cover classes of T (0 to 0.5 percent of the plot); 1 (0.5 to 5 percent); 2 (5 to 25 percent); 3 (25 to 50 percent); 4 (50 to 75 percent); 5 (75 to 95 percent); and 6 (95 to 100 percent). Midpoint values for these classes are 0.2, 2.5, 15, 37.5, 62.5, 85, and 97.5 percent, respectively. Presence/absence tallies were used to

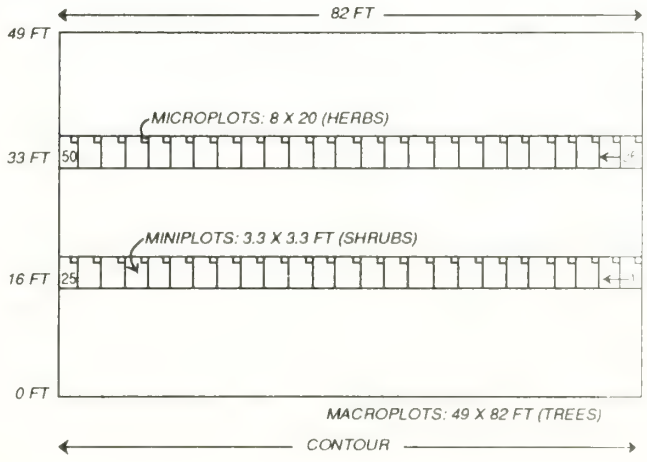

Figure 3—Plot layout for macroplot, miniplots, and microplots for the Silver Creek vegetation study.

determine frequency, which is the percentage of microplots in which a species occurs. Rooted frequency provides an indication of a plant species' rooted distribution or occurrence within the macroplot.

Miniplot

Shrub species were sampled in the miniplots for rooted frequency and canopy coverage using the same classes as for the microplots. Average height of each shrub species rooted within the plots was estimated to the nearest foot.

Macroplot

Trees and site features (percentage slope, aspect, elevation, slope position, and microrelief of the soil surface) were sampled in the macroplot. All trees greater than 4.5 ft tall were tallied by species in 4-inch d.b.h. classes to 40 inches as 0 to 4 inches, 5 to 8 inches, and so forth.

To assess the response of vegetation to helicopter logging and burning, five samplings were made over 10 years, from 1976 to 1986. These included predisturbance (1976) and 1-, 2-, 5-, and 10-year postdisturbance (1977 to 1986) remeasurements.

RESULTS AND DISCUSSION

Predisturbance vegetation on the 12 plots was similar, so results from the two habitat types are grouped. Within each macroplot, miniplots and microplots were designated as burned or unburned and are summarized separately. Over all three cutting units, 52 percent of the microplots were burned while 48 percent were unburned. Results from cutting units 4 and 5 are grouped based on the Ryan-Noste (1985) fire severity rating but are separate for cutting unit 6, which received a separate rating. Number of trees per acre and basal area per acre are summarized in table 1. Shrub cover, frequency, and height were summarized as well as forb cover and frequency. Results are shown tabularly and graphically for major species.

Trees

The overstory was dominated by *Pinus ponderosa* both before and after the disturbance (table 1). Some smaller trees not removed by the harvesting later died as a consequence of the broadcast burning, resulting in a decline in the number of trees per acre through time. Seedling recruitment into the stand was minimal. After 10 years only a few seedlings were found in the plots (table 1). In most cases, restocking by natural regeneration would be desired following helicopter logging. However, because of the prescription on this study area, no seedbearing trees were left in the cutting units and many of the trees adjacent to the plots were overmature and producing little seed.

Shrubs

The climax shrubs, *Physocarpus malvaceus* and *Spiraea betulifolia* were dominant in all three cutting units prior to the disturbance. Immediately following the disturbance, shrub cover (fig. 4, table 2) and root frequency (table 3) were lower on burned plots compared to unburned plots. However, the shrub composition was not altered. Total cover and frequency on cutting units 4/5, and the unburned plots in cutting unit 6, increased up to year 5, then declined at year 10 and in most cases were well below the predisturbance level. In cutting unit 6, total shrub cover and frequency on burned plots increased every sample year following the disturbance, but this was due primarily to an increase in *Ceanothus velutinus*.

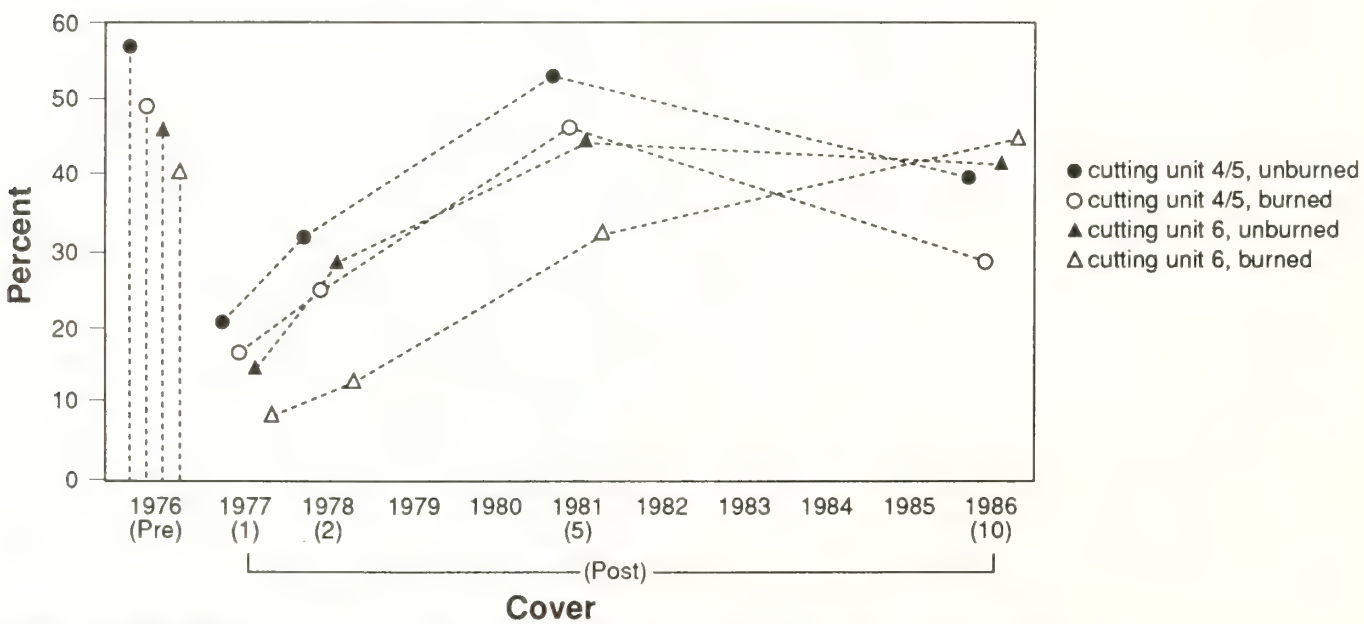

Figure 4—Cover (percent) of all shrubs in unburned and burned plots in cutting units 4/5 and 6 predisturbance (pre) and postdisturbance, (1), (2), (5), and (10) years after disturbance.

Table 2—Shrub cover (percent) by years for unburned and burned miniplots in cutting units 4/5 and 6

Species	Year	Unit 4/5		Unit 6	
		Unburned	Burned	Unburned	Burned
		Percent			
Amelanchier alnifolia	Pre[1]	1	1	0	1
	1	1	[2]1*	0	0
	2	1	1*	0	0
	5	2	1	1*	1*
	10	2	1	1	1*
Berberis repens	Pre	1*	1*	4	3
	1	1*	1*	1	1*
	2	1*	1*	2	1*
	5	1	1	2	1
	10	1	1*	2	2
Ceanothus velutinus	Pre	1	1*	0	2
	1	0	1	1	1
	2	1*	1	0	1
	5	1	1	1*	9
	10	1	4	1*	22
Physocarpus malvaceus	Pre	22	21	22	22
	1	8	6	7	3
	2	10	8	16	7
	5	17	17	27	14
	10	10	9	24	10
Prunus emarginata	Pre	1	1*	2	2
	1	1*	0	1	1*
	2	1	0	2	0
	5	1	1*	3	1*
	10	3	1	3	1*
Prunus virginiana	Pre	2	1	9	1
	1	1	1*	1	1*
	2	2	1*	2	1*
	5	2	1*	3	1*
	10	1	1	3	1*
Ribes spp.	Pre	1	0	0	0
	1	0	0	0	0
	2	1*	0	0	0
	5	1*	0	0	1*
	10	1*	0	1*	1*
Rosa spp.	Pre	2	1	2	2
	1	1	1*	1*	1*
	2	1	1*	1	1*
	5	1	1	3	1
	10	1	1	1	1
Salix scouleriana	Pre	4	0	1	1
	1	2	0	1	0
	2	3	0	1	1*
	5	5	1*	2	2
	10	8	1*	2	3
Spiraea betulifolia	Pre	20	21	4	6
	1	5	6	1	1
	2	10	12	3	1
	5	16	19	2	2
	10	7	7	3	3

(con.)

Table 2 (Con.)

Species	Year	Unit 4/5		Unit 6	
		Unburned	Burned	Unburned	Burned
		Percent			
Symphoricarpos albus	Pre	1	1	0	0
	1	1	1*	0	0
	2	1	1	0	0
	5	3	3	0	0
	10	3	3	0	0
Symphoricarpos oreophilus	Pre	1	1	1*	1*
	1	1	1	1*	1*
	2	1	1	1*	1*
	5	3	1	1	1
	10	2	1	1	1*
Total	Pre	57	49	45	40
	1	21	17	14	8
	2	32	25	28	12
	5	53	46	44	32
	10	40	29	41	44

[1]Pre is predisturbance, 1 is 1 year after disturbance, and so forth.
[2]1* is less than 1 percent.

Table 3—Root frequency (percent) of shrubs by years for unburned and burned miniplots in cutting units 4/5 and 6

Species	Year	Unit 4/5		Unit 6	
		Unburned	Burned	Unburned	Burned
		Percent			
Amelanchier alnifolia	Pre[1]	6	2	0	2
	1	6	2	0	1
	2	5	1	0	1
	5	5	3	0	1
	10	7	4	2	2
Berberis repens	Pre	4	6	37	27
	1	2	4	31	6
	2	2	3	30	12
	5	7	6	32	15
	10	7	8	38	17
Ceanothus velutinus	Pre	1	1	0	2
	1	[2]1*	6	0	27
	2	2	8	0	21
	5	2	5	0	28
	10	2	9	0	29
Physocarpus malvaceus	Pre	40	36	47	44
	1	40	30	47	30
	2	41	34	47	32
	5	44	36	49	36
	10	42	36	50	35
Prunus emarginata	Pre	1	1*	3	2
	1	1	0	3	1
	2	0	0	3	1
	5	2	1	3	1
	10	4	1	3	1

(con.)

Table 3 (Con.)

Species	Year	Unit 4/5		Unit 6	
		Unburned	Burned	Unburned	Burned
		Percent			
Prunus virginiana	Pre	10	10	30	10
	1	9	5	30	6
	2	9	6	22	8
	5	10	5	20	7
	10	8	6	20	5
Ribes spp.	Pre	1	1*	0	0
	1	0	0	0	0
	2	2	0	0	0
	5	2	0	0	1
	10	2	1	1	1
Rosa spp.	Pre	13	7	10	9
	1	13	4	10	5
	2	12	8	10	7
	5	14	10	10	8
	10	16	11	11	8
Salix scouleriana	Pre	6	0	1	1
	1	6	0	1	0
	2	5	0	1	0
	5	5	0	1	0
	10	5	1	1	1
Spiraea betulifolia	Pre	79	80	30	36
	1	77	71	37	23
	2	76	78	41	24
	5	84	85	33	28
	10	77	76	33	32
Symphoricarpos albus	Pre	9	9	0	0
	1	12	8	0	0
	2	13	9	0	0
	5	14	15	0	0
	10	18	20	0	0
Symphoricarpos oreophilus	Pre	2	2	2	2
	1	8	3	8	2
	2	6	3	4	3
	5	11	4	4	4
	10	10	4	9	2

[1]Pre is predisturbance, 1 is 1 year after disturbance, and so forth.
[2]1* is less than 1 percent.

At year 10, *Ceanothus* cover exceeded both *Physocarpus* and *Spiraea* cover on burned plots in cutting unit 6, while in unburned areas, and in all of cutting units 4/5, shrub composition after 10 years was similar to the predisturbance composition. The large decline in shrubs at 10 years is not understood but may be related to the extremely dry (half the normal precipitation) weather conditions the year of the sampling.

Ceanothus velutinus—This is an early seral, shade-intolerant shrub (Steele and Geier-Hayes 1986, 1987). It was present in the predisturbance shrub community in small amounts in all three cutting units. When burned and unburned plots were compared, *Ceanothus* was absent initially only on unburned plots in cutting unit 6 (fig. 5, table 3). Postdisturbance, *Ceanothus* cover and frequency barely increased on unburned plots in cutting units 4/5 and was never found rooted in unburned plots in cutting unit 6 (tables 2, 3). Cover and frequency of *Ceanothus* on burned plots in cutting units 4/5 increased slightly. However, increase of *Ceanothus* was dramatic in cutting unit 6 on burned plots. *Ceanothus* is a nonrhizomatous shrub that can survive burning (Stickney 1985) and will resprout from the root crown. *Ceanothus* can also germinate from seeds buried in the soil for as long as 200 to 250 years (Conard and others 1985). Seeds require

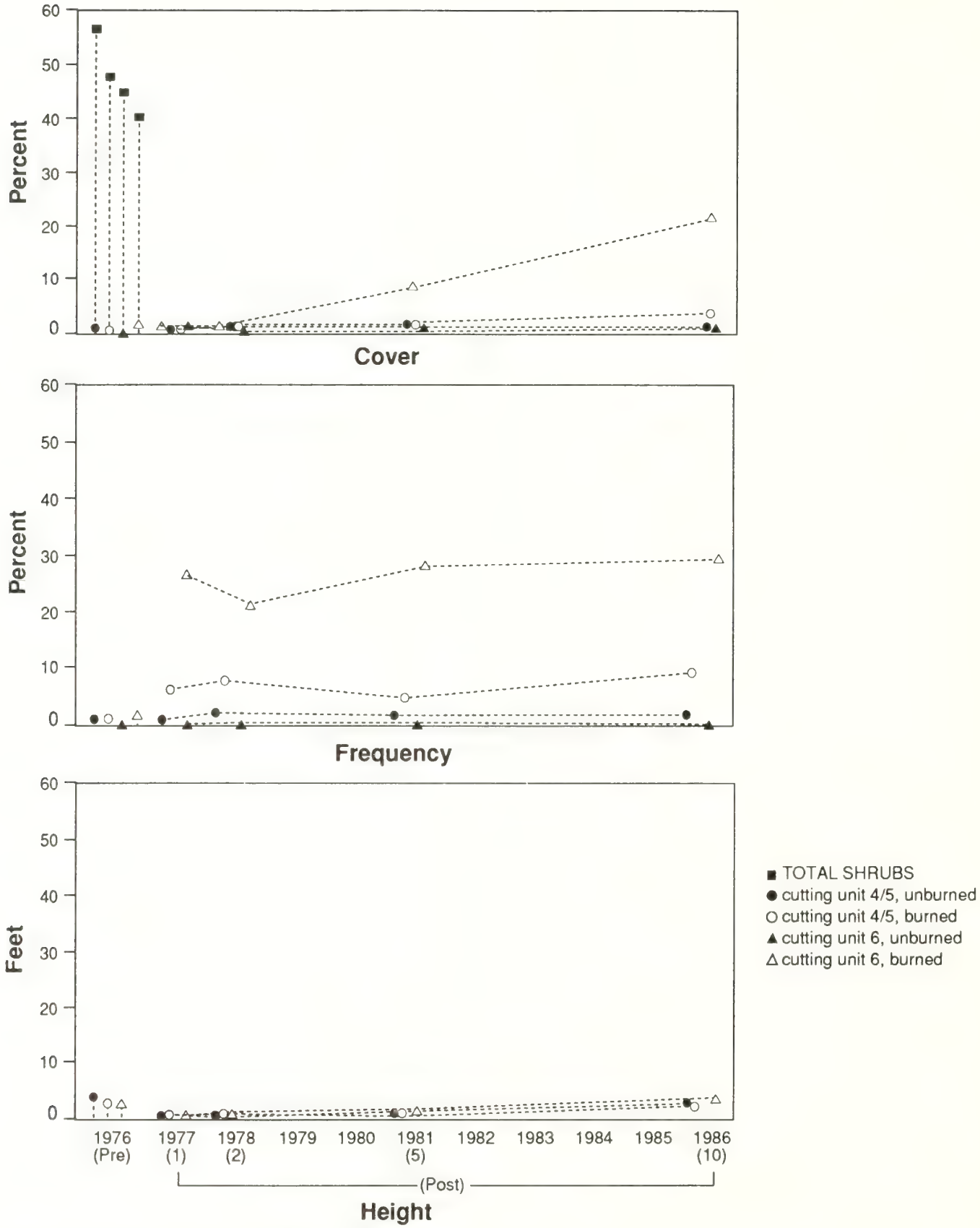

Figure 5—Cover (percent), frequency (percent), and height (feet) of *Ceanothus velutinus* in unburned and burned plots in cutting units 4/5 and 6 predisturbance (pre) and postdisturbance, (1), (2), (5), and (10) years after disturbance.

others 1985). Seeds require heat to break dormancy, and burning often stimulates germination. Lack of germination in cutting units 4/5 may have been due to a lack of seed in the soil. However, presence of shrubs in the predisturbance community often indicates a seed source (Keane 1987). Low germination in cutting units 4/5 is more likely due to the lower severity burning, whereas in cutting unit 6, the burning appears to have been severe enough to trigger *Ceanothus* germination. Shrubs in cutting unit 6 were also taller than the predisturbance shrubs after 10 years, while those on cutting units 4/5 were shorter (table 4).

Physocarpus malvaceus—Cover and height of *Physocarpus* was the same on all cutting units before the disturbance (table 2, 4), though frequency was slightly higher in cutting unit 6 (table 3). Ten years after the disturbance, cover and frequency were not much different than the predisturbance on both burned and unburned plots in cutting units 4/5 (fig. 6). In cutting unit 6, however, cover, frequency, and height were increased on unburned plots after 10 years compared to the predisturbance even though cover peaked 5 years after the disturbance. In the burned plots in cutting unit 6, recovery was slower. Cover was only 64 percent of predisturbance level 5 years after the disturbance and 46 percent after 10 years. Frequency was 80 percent of the predisturbance frequency after 10 years.

Table 4—Height (feet) by years for shrubs in unburned and burned miniplots in cutting units 4/5 and unit 6

Species	Year	Unit 4/5		Unit 6	
		Unburned	Burned	Unburned	Burned
		Feet			
Amelanchier alnifolia	Pre[1]	2.9	2.9	0	3.2
	1	.9	1.0	0	1.6
	2	1.1	1.0	0	1.5
	5	1.8	2.1	0	1.3
	10	3.4	2.9	3.3	2.8
Berberis repens	Pre	.6	.5	.9	9
	1	.4	.3	.7	4
	2	.4	.4	.6	5
	5	.4	.5	.5	.5
	10	1.1	1.1	.9	1.0
Ceanothus velutinus	Pre	4.1	3.1	0	3.1
	1	.7	.4	0	3
	2	.6	.3	0	.3
	5	1.1	1.1	0	1.5
	10	3.2	2.6	0	4.2
Physocarpus malvaceus	Pre	2.4	2.5	2.1	2.3
	1	1.4	1.3	1.8	1.2
	2	1.6	1.4	1.6	1.3
	5	2.0	1.8	2.0	1.9
	10	2.5	2.4	3.1	2.9
Prunus emarginata	Pre	6.8	3.0	7.5	4.4
	1	2.0	0	3.1	1.0
	2	0	0	2.7	5
	5	3.6	2.5	5.0	2.7
	10	3.7	3.8	6.1	4.4
Prunus virginiana	Pre	1.6	1.5	2.0	1.3
	1	1.0	.7	.7	.7
	2	1.0	.9	1.1	1.0
	5	1.4	1.5	1.6	1.3
	10	2.8	2.2	2.2	2.2
Ribes spp.	Pre	2.6	3.3	0	0
	1	0	0	0	0
	2	.9	0	0	0
	5	1.4	0	0	2.6
	10	1.9	.3	3.4	3.4

(con.)

Table 4 (Con.)

Species	Year	Unit 4/5		Unit 6	
		Unburned	Burned	Unburned	Burned
		Feet			
Rosa spp.	Pre	1.3	1.5	1.8	2.3
	1	.9	.9	.5	1.0
	2	.9	.9	.7	.8
	5	1.0	1.2	1.0	.9
	10	1.6	2.1	2.1	2.0
Salix scouleriana	Pre	6.8	0	6.6	8.0
	1	2.3	0	4.6	0
	2	3.8	0	2.8	0
	5	5.8	0	5.8	0
	10	6.9	5.1	6.5	9.8
Spiraea betulifolia	Pre	.9	.9	.7	.8
	1	.8	.8	.6	.6
	2	.7	.6	.7	.6
	5	.8	.8	.8	.7
	10	1.1	1.1	.9	1.1
Symphoricarpos albus	Pre	1.3	1.2	0	0
	1	.9	.9	0	0
	2	1.0	.7	0	0
	5	1.2	1.3	0	0
	10	1.7	1.6	0	0
Symphoricarpos oreophilus	Pre	1.9	2.5	1.6	1.2
	1	1.3	1.3	.5	.8
	2	1.3	1.1	1.0	1.0
	5	1.6	1.4	1.8	1.6
	10	2.2	2.3	2.3	1.6

[1]Pre is predisturbance, 1 is 1 year after disturbance, and so forth.

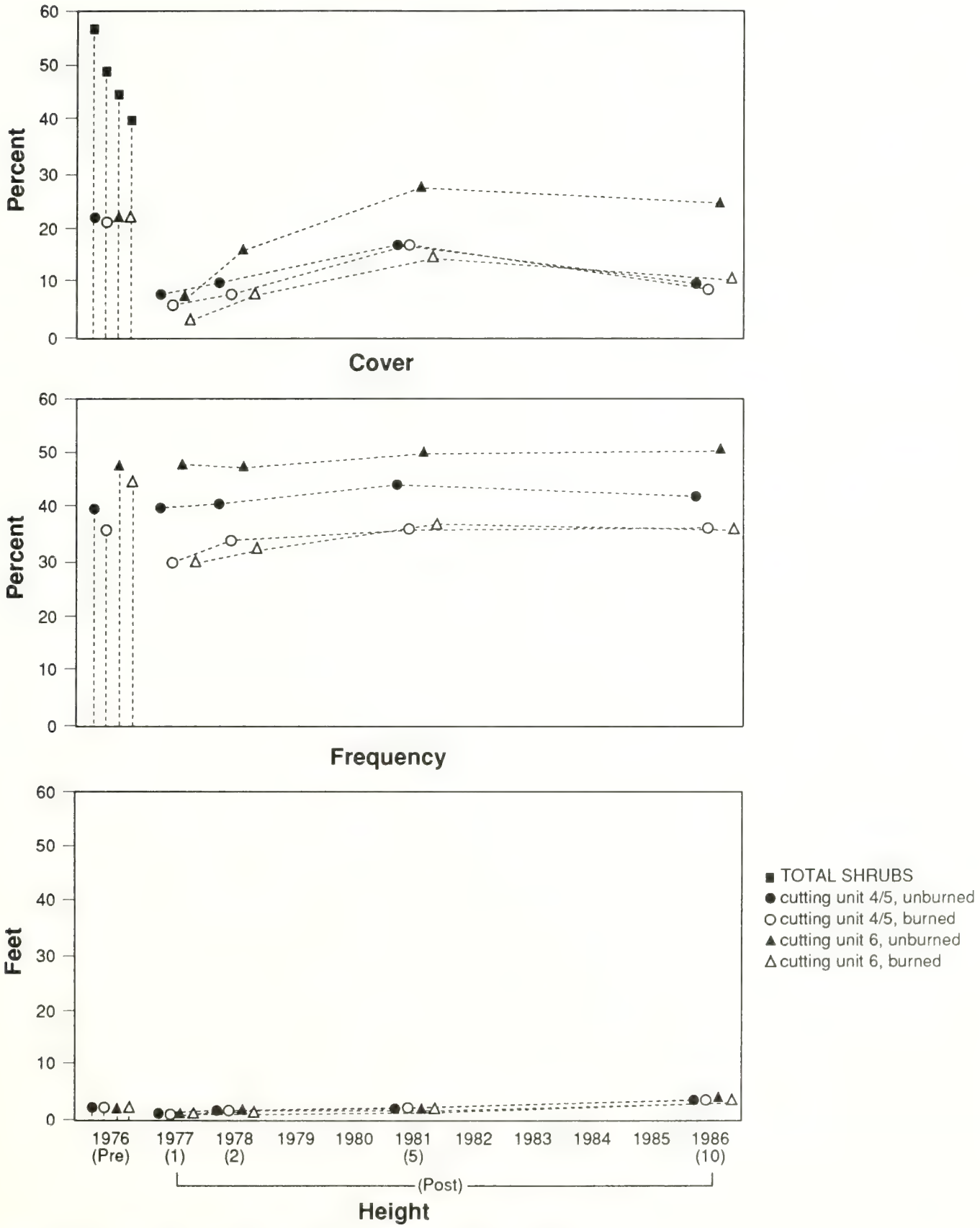

Figure 6—Cover (percent), frequency (percent), and height (feet) of *Physocarpus malvaceus* in unburned and burned plots in cutting units 4/5 and 6 predisturbance (pre) and postdisturbance, (1), (2), (5), and (10) years after disturbance.

Physocarpus malvaceus is the climax shrub species in the *Pseudotsuga menziesii / Physocarpus malvaceus* habitat type and is capable of resprouting from root crowns after burning (Crane and others 1983). It spreads by way of root sprouts (Steele and Geier-Hayes 1987). Although the lower severity burning on cutting units 4 and 5 appears to have had little effect on *Physocarpus*, the higher severity burning on cutting unit 6 may have retarded the shrub. Arno and others (1985) noted a similar decline of *Physocarpus malvaceus* on dry sites in western Montana.

Spiraea betulifolia—This is the climax shrub in the *Pseudotsuga menziesii / Spiraea betulifolia* habitat type and is also common in the *Pseudotsuga menziesii / Physocarpus malvaceus* habitat type. Cover and frequency of *Spiraea* was much higher in cutting units 4/5 than in cutting unit 6 before the disturbance (tables 2, 4). There was little difference between the burned and unburned plots within each cutting unit both before the disturbance and 10 years later (fig. 7). Cover on cutting units 4/5 peaked 5 years after the disturbance when cover was 80 percent of the predisturbance level on unburned plots and 90 percent on burned. At 10 years, however, cover was only 35 percent of the predisturbance cover. This dramatic decline does not appear to be related to the disturbance. Frequency of *Spiraea* was not much different between burned and unburned plot after 10 years. In most cases, it was only slightly lower than predisturbance on all plots except the unburned plots in cutting unit 6, where frequency was slightly higher. As with cover, frequency peaked 5 years after the disturbance in cutting units 4/5. However, on unburned plots in cutting unit 6, frequency peaked 2 years after disturbance, and on burned plots, was highest at 10 years. *Spiraea* is a rhizomatous shrub that not only usually survives burning but can often flower the year immediately following burning (Crane and others 1983; Stickney 1985).

Symphoricarpos albus—This shade-tolerant, rhizomatous shrub is found primarily in the *Pseudotsuga menziesii / Physocarpus malvaceus* habitat type. It is uncommon in the *Pseudotsuga menziesii / Spiraea betulifolia* habitat type, though *Symphoricarpos oreophilus*, a nonrhizomatous shrub, is often present (table 3). *Symphoricarpos albus* is usually restricted to moist areas, even within the *Pseudotsuga menziesii / Physocarpus malvaceus* habitat type, and none was found in cutting unit 6, which is possible slightly drier due to its position in the drainage. In cutting units 4/5, there is no difference in the cover or height of *Symphoricarpos albus* on burned and unburned plots (tables 2, 4, fig. 8) . Cover before the disturbance and 10 years later was the same on burned and underburned plots, though cover had increased slightly after 10 years compared to the predisturbance cover. Frequency, however, increased dramatically over the predisturbance level on both burned and unburned plots though the spread was slightly slower on the burned plots. *Symphoricarpos albus* can survive burning and can spread following burning by way of its rhizomes.

Salix scouleriana—*Salix* was present in all cutting units before and after the disturbance, though none was present in cutting units 4/5 in the predisturbance plots which were burned (table 3). Following the disturbance, two seedlings were found on burned plots in cutting unit 4. Cover of *Salix* on unburned plots in cutting units 4/5 increased slightly, but there was little difference between burned and unburned plots in cutting unit 6 (table 2, fig. 9). *Salix*, a nonrhizomatous shrub, can attain heights as tall as 15 to 25 ft in the *Pseudotsuga menziesii / Physocarpus malvaceus* h.t. (Steele and Geier-Hayes 1987) and 10 to 14 ft in the *Pseudotsuga menziesii / Spiraea betulifolia* h.t. (Steele and Geier-Hayes 1986). However, in this study area the average height was 7 ft on all cutting units (table 4). It is capable of resprouting following burning (Stickney 1985) and can seed in moist mineral soil (Steele and Geier-Hayes 1986, 1987). In this study area, burning had little effect on the shrub.

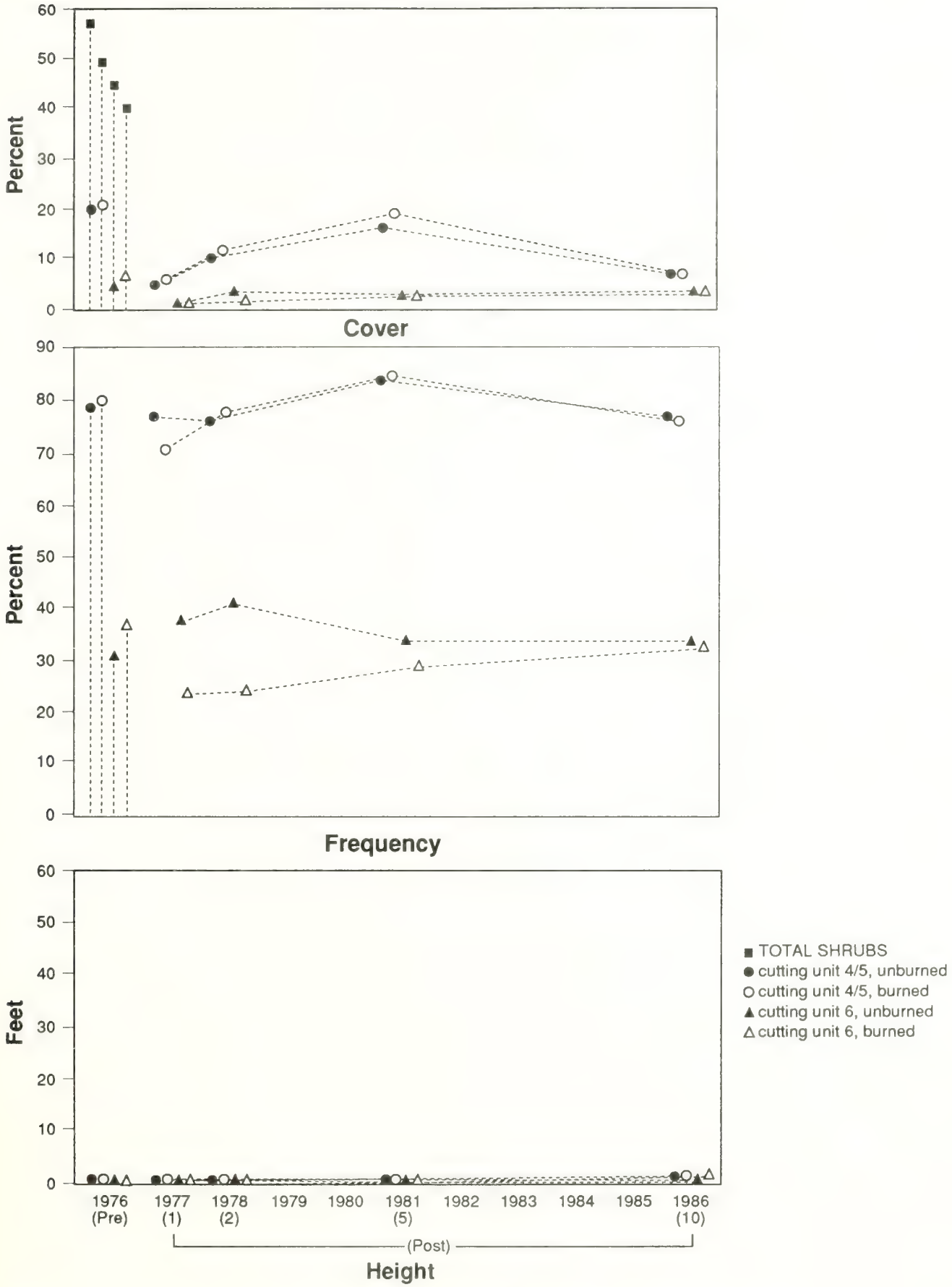

Figure 7—Cover (percent), frequency (percent), and height (feet) of *Spiraea betulifolia* in unburned and burned plots in cutting units 4/5 and 6 predisturbance (pre) and postdisturbance, (1), (2), (5), and (10) years after disturbance.

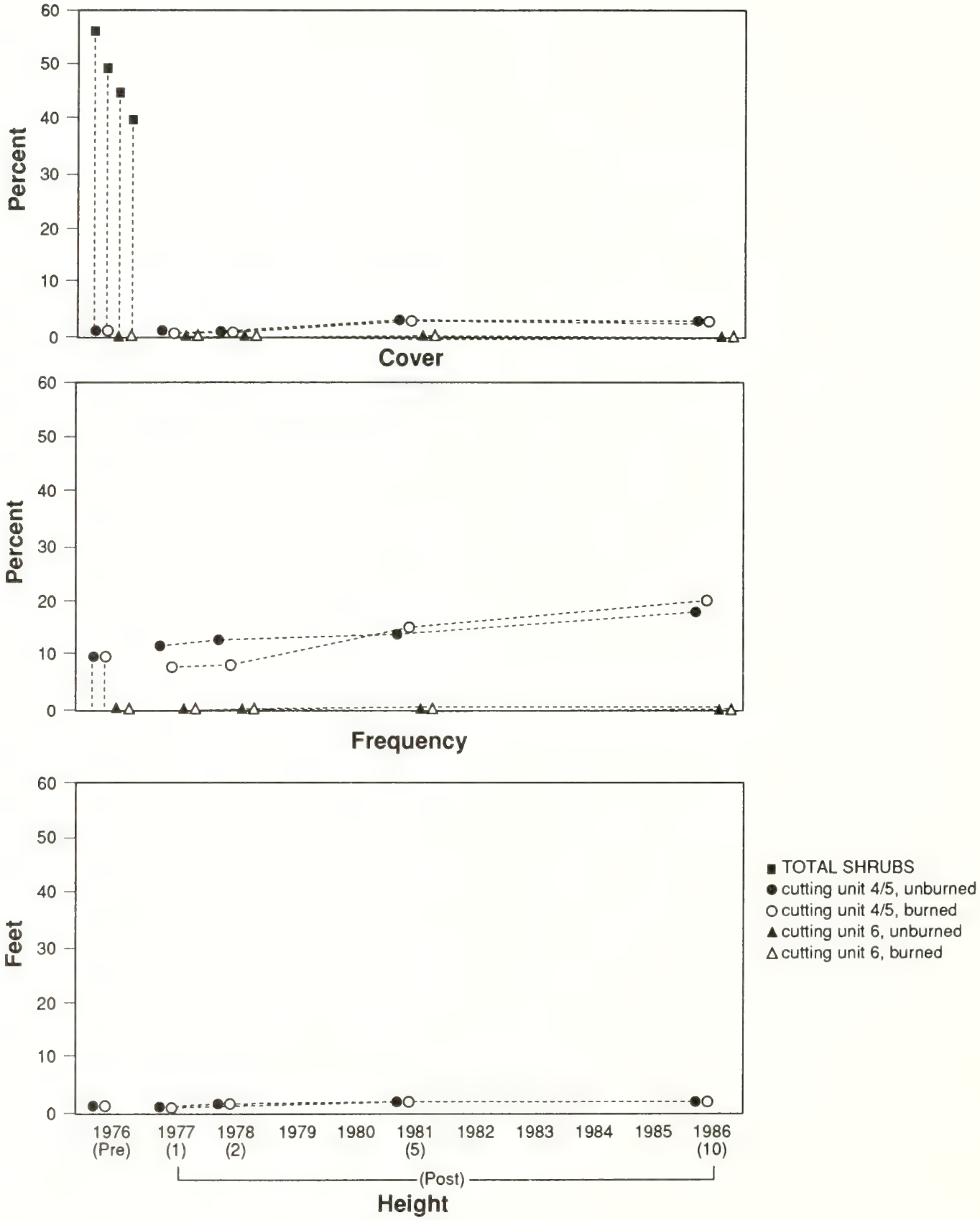

Figure 8—Cover (percent), frequency (percent), and height (feet) of *Symphoricarpos albus* in unburned and burned plots in cutting units 4/5 and 6 predisturbance (pre) and postdisturbance, (1), (2), (5), and (10) years after disturbance.

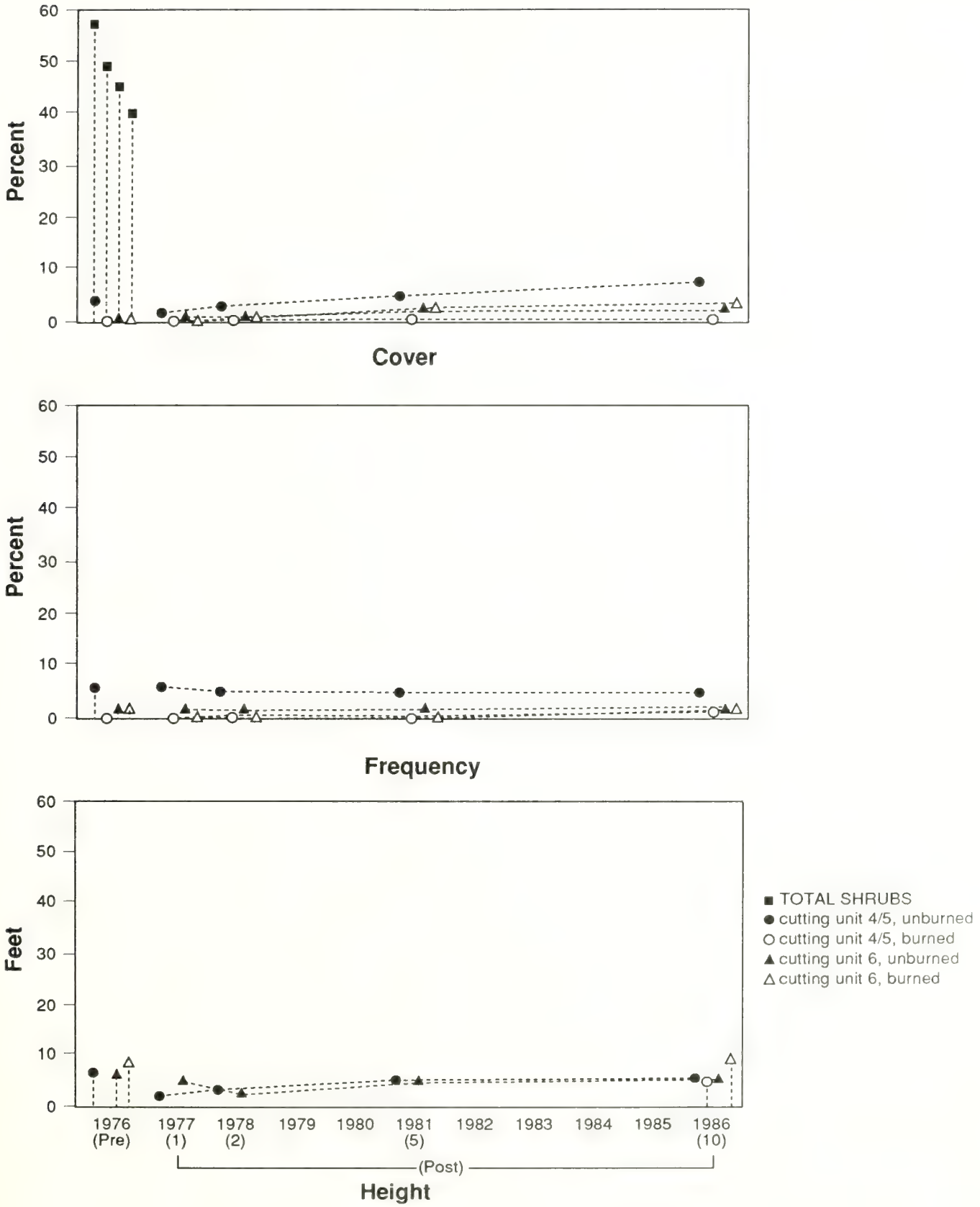

Figure 9—Cover (percent), frequency (percent), and height (feet) of *Salix scouleriana* in unburned and burned plots in cutting units 4/5 and 6 predisturbance (pre) and postdisturbance, (1), (2), (5), and (10) years after disturbance.

Herbs

The predisturbance herbaceous community was dominated by the graminoids *Calamagrostis rubescens* and *Carex geyeri* and by the forb *Lathyrus nevadensis* (tables 5, 6). *Calamagrostis* was restricted to cutting units 4/5 while *Carex geyeri* was more common in cutting unit 6. Total cover of herbs (forbs and graminoids) was similar on burned and unburned plots within each cutting unit. However, total herb cover was higher in cutting units 4/5 than in cutting unit 6 (table 5, fig. 10). Total cover was not much different between burned and unburned plots on cutting units 4/5 after the disturbance. On cutting unit 6, at 10 years, total cover was nearly the same between burned and unburned plots, but recovery of herbs was slow. The year immediately following the burning, herb cover on unburned plots was 80 percent of the predisturbance cover, while on burned plots herb cover was only 50 percent of the predisturbance. At year 5, total cover on both burned and unburned plots exceeded predisturbance cover. However, total cover on unburned plots was 67 percent of the area compared to 43 percent cover on burned plots.

Composition of the herbaceous community was altered by the disturbance in most cutting units. Annuals, primarily species of *Collinsia, Cryptantha, Gayophytum, Clarkia*, and *Collomia* as well as the short-lived perennials such as *Phacelia*, will often occur on newly exposed mineral soil (Steele and Geier-Hayes 1986, 1987). Though annuals and short-lived perennials were found in the predisturbance community in only small amounts before the disturbance, they as a group began to attain high coverages immediately following the disturbance, particularly in cutting unit 6. By year 5, annuals and short-lived perennials were detected in every burned plot in cutting units 4/5 and in every plot in cutting unit 6 (table 6).

Though cover and frequency of annuals and short-lived perennials were low at year 10, this may have been due to the weather conditions because many annuals appear and flower early in the summer, and dry summer weather may have accelerated the loss before the sampling was conducted.

Herb cover for all cutting units was highest at year 5 when cover exceeded the predisturbance cover. Herb cover had declined at year 10. Again, the reason is not understood, but if drought were influencing the vegetation, the herbaceous vegetation is likely the most affected because much of its biomass is regrown each year.

Table 5—Herb cover (percent) by years for unburned and burned microplots in cutting units 4/5 and 6

Species	Year	Unit 4/5		Unit 6	
		Unburned	Burned	Unburned	Burned
Apocynum androsaemifolium	Pre[1]	1	1	1	1
	1	1	1	2	1
	2	[2]1*	1	1	1
	5	1	2	2	3
	10	1	2	1	2
Arenaria macrophylla	Pre	3	2	4	2
	1	1	2	1	1
	2	2	1	5	2
	5	2	1	7	1
	10	1*	1*	0	0
Arnica cordifolia	Pre	4	4	1	1
	1	2	3	1*	1
	2	5	5	1	2
	5	4	3	1	1
	10	0	0	0	0
Calamagrostis rubescens	Pre	13	13	0	0
	1	6	5	0	0
	2	17	12	0	0
	5	26	24	0	0
	10	8	8	0	0
Carex geyeri	Pre	3	4	10	10
	1	2	1	4	2
	2	4	4	12	5
	5	9	8	23	11
	10	10	7	15	9

(con.)

Table 5 (Con.)

Species	Year	Unit 4/5		Unit 6	
		Unburned	Burned	Unburned	Burned
Lathyrus nevadensis	Pre	12	14	4	4
	1	6	7	2	1
	2	9	7	3	1
	5	3	2	1	0
	10	1	1	1	1*
Thalictrum occidentale	Pre	3	1	0	1*
	1	1	1	0	0
	2	2	1	0	0
	5	3	1	0	0
	10	2	1*	0	0
Misc.	Pre	3	3	4	3
	1	4	1	3	2
	2	9	6	8	9
	5	10	9	6	4
	10	6	5	3	4
Annuals and short-lived perennials	Pre	0	1*	1	1*
	1	1*	1	8	3
	2	4	7	19	12
	5	10	17	27	23
	10	4	5	1	2
Totals	Pre	42	42	25	22
	1	23	22	20	11
	2	52	44	49	32
	5	68	67	67	43
	10	32	29	21	17

[1]Pre is predisturbance, 1 is 1 year after disturbance, and so forth.
[2]1* is less than 1 percent.

Table 6—Rooted frequency (percent) for herbs by years in unburned and burned microplots in cutting units 4/5 and 6

Species	Year	Unit 4/5		Unit 6	
		Unburned	Burned	Unburned	Burned
Apocynum androsaemifolium	Pre[1]	6	3	2	7
	1	5	7	1	3
	2	3	4	8	7
	5	7	8	18	17
	10	6	9	6	14
Arenaria macrophylla	Pre	23	21	31	22
	1	18	20	25	9
	2	27	16	41	17
	5	20	19	52	12
	10	6	4	0	0
Arnica cordifolia	Pre	25	17	5	7
	1	27	25	5	11
	2	47	37	5	15
	5	35	24	8	8
	10	0	1	0	0
Calamagrostis rubescens	Pre	46	43	0	0
	1	36	32	0	0
	2	43	30	0	0
	5	50	42	0	0
	10	39	39	0	0

(con.)

Table 6 (Con.)

Species	Year	Unit 4/5		Unit 6	
		Unburned	Burned	Unburned	Burned
Carex geyeri	Pre	11	13	36	33
	1	9	4	30	15
	2	8	12	32	13
	5	18	16	38	19
	10	20	10	32	22
Lathyrus nevadensis	Pre	53	59	29	25
	1	52	48	27	11
	2	59	52	22	12
	5	34	17	7	6
	10	23	18	8	2
Thalictrum occidentale	Pre	9	4	0	2
	1	6	5	0	0
	2	8	4	0	0
	5	8	4	0	0
	10	10	6	0	0
Misc.	Pre	10	10	8	0
	1	8	1	8	4
	2	36	25	14	7
	5	23	18	24	13
	10	10	14	13	1
Annuals and short lived perennials	Pre	8	0	0	1
	1	5	9	25	15
	2	34	40	49	52
	5	61	100	100	100
	10	55	79	34	33

[1]Pre is predisturbance, 1 is 1 year after disturbance, and so forth.

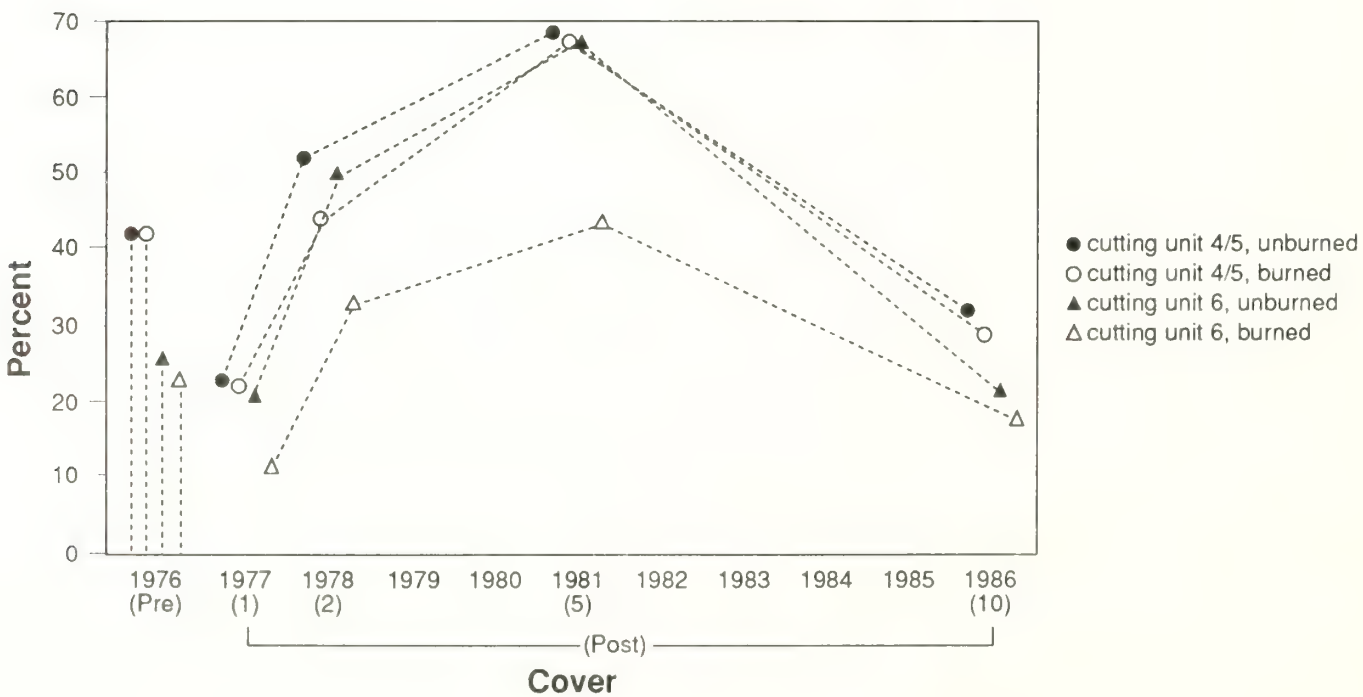

Figure 10—Cover (percent) of all herbs in unburned and burned plots in cutting units 4/5 and 6 predisturbance (pre) and postdisturbance, (1), (2), (5), and (10) years after disturbance.

Calamagrostis rubescens—This was the dominant graminoid in cutting units 4/5 in the predisturbance community. None was found in cutting unit 6 (tables 5, 6). Cover on burned and unburned plots after the disturbance was only slightly different. At years 5 and 10 the cover was nearly the same on both burned and unburned areas (table 5, fig. 11). Frequency and cover of *Calamagrostis* was highest in year 5 and much lower in year 10. The decline does not seem related to the disturbance. *Calamagrostis rubescens* is a rhizomatous grass that can usually survive burning (Crane and others 1983; Stickney 1985). Both Crane and others (1983) and Stickney (1985) found *Calamagrostis* blooming the year immediately following burning on their study areas.

Carex geyeri—This was present in small amounts in cutting units 4/5 and was the dominant graminoid in cutting unit 6 (tables 5, 6). While there was little difference in cover of *Carex* on burned and unburned plots in cutting units 4/5, larger cover increases of *Carex* occurred on unburned plots compared to burned plots in cutting unit 6 (table 5, fig. 12).

The cover in the predisturbance community was the same, but cover on burned plots was only half the cover on unburned plots the year immediately following the burning, 2 years later, and 5 years later. At 10 years, cover on burned plots was 60 percent of the unburned plots. Frequency of *Carex geyeri* immediately following the disturbance was also about half of the unburned plots following the disturbance, though in the predisturbance community frequency was nearly the same (table 6).

Carex geyeri has an extensive root system, but the root crowns are close to the soil surface. The burning in cutting unit 6 may have heated the soil enough to damage or destroy the root crowns, which then retarded the regrowth. In cutting units 4/5, the less severe burning does not appear to have had the same effect on the *Carex*.

Lathyrus nevadensis—This was the dominant forb iin all three cutting units before the disturbance, though coverages were higher in cutting units 4/5 (tables 5, 6). The year immediately following the disturbance, cover was half that of predisturbance on both burned and unburned plots in all three cutting units (table 5, fig. 13). Frequency, however, barely changed the year following the disturbance on unburned plots in cutting units 4/5 and actually increased in unburned plots in cutting unit 6 (table 6). On burned plots in cutting units 4/5, frequency declined only slightly. However, on burned plots in cutting unit 6, frequency was only half that of predisturbance. Cover increased slightly on unburned plots in all cutting units by the second year following the disturbance, but cover on all plots then declined by year 5 and was even lower by year 10. The trend was similar for frequency; on many plots, frequency peaked after 2 years, then declined at years 5 and 10.

When present, *Lathyrus* is usually found in the near-climax community (Steele and Geier-Hayes 1987). A shade-tolerant forb, it may not be capable of sustaining high coverages under the extreme environmental conditions created by clearcutting. Even though the total cover of shrubs increased each year to year 5 following the disturbance, loss of overstory usually results in increased amounts of solar radiation and heating on the site even with the shrub cover.

Arnica cordifolia—This was present in all three cutting units (table 6), but had higher coverages in cutting units 4/5 (table 5). Though cover was small, frequencies were high. The pattern of change through time was similar to *Lathyrus*; cover and frequency of *Arnica* increased up to 2 years following the disturbance, then began to decline (fig. 14). Like *Lathyrus, Arnica* often attains highest coverages in late seral communities (Steele and Geier-Hayes 1987), though it can also be present in early seral communities.

CONCLUSIONS

The severity of the burning in cutting units 4/5 rated a 2-M using the Ryan-Noste (1985) fire severity rating, while the burning in cutting unit 6 attained a 3-M. Burning in cutting units 4/5 took place spring 1977 with some snow present on the site, while the burning in cutting unit 6 took place in winter 1976, before any snow had fallen. Recovery of vegetation on burned and unburned areas in cutting units 4/5 was similar, and after 10 years, vegetation in both burned and unburned plots was almost the same. In cutting unit 6, however, vegetation differed between burned and unburned plots. In the unburned areas, the vegetation resembled that found on plots in cutting units 4/5. But on burned plots, after 10 years the vegetation was dominated by *Ceanothus velutinus*.

Most vegetation in the area before the disturbance resprouted following the harvesting and burning. *Physocarpus malvaceus* and *Spiraea betulifolia* dominated the vegetation before the disturbance, and both were still prominent on burned/unburned plots in cutting units 4/5, and in unburned plots in cutting unit 6. In burned plots in cutting unit 6, *Ceanothus velutinus* dominated after 10 years. The only shrub other than *Ceanothus* that increased on the study area was *Symphoricarpos albus*, which increased in frequency in cutting units 4/5. Over the 10 years, many shrubs peaked in cover and frequency 5 years after the disturbance. However, this peak may be related to the weather conditions the summer of the sampling rather than to the disturbance.

Recovery of *Physocarpus malvaceus* was slow on the burned plots in cutting unit 6 compared to the unburned plots in unit 6 and to both burned and unburned plots in cutting units 4/5. The *Physocarpus malvaceus* may have been retarded by the higher soil heating that took place in cutting unit 6. No other shrubs present before the disturbance were affected like *Physocarpus*, but the burning was hot enough to stimulate the germination of *Ceanothus*, which did not attain high coverages in the other cutting units.

As with the shrubs, many of the herbs present before the disturbance resprouted following the burning. Annuals increased on many plots, both burned and unburned. However, their individual coverages are small even though annuals were found on almost every plot in the study area at year 5. *Calamagrostis rubescens* and *Carex geyeri*, both graminoids, were the dominant herbs in the

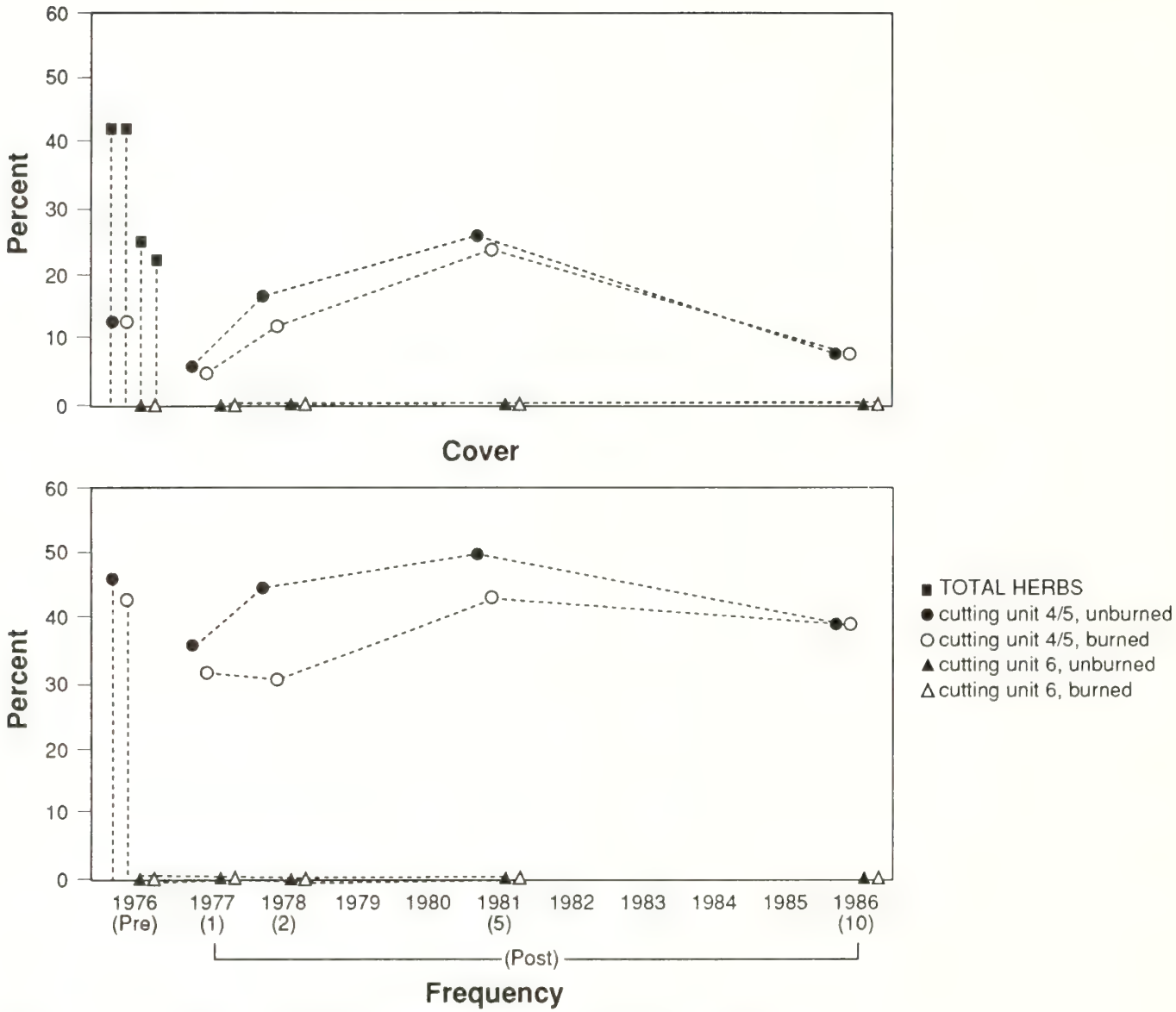

Figure 11—Cover (percent) and frequency (percent) of *Calamagrostis rubescens* in unburned and burned plots in cutting units 4/5 and 6 predisturbance (pre) and postdisturbance, (1), (2), (5), and (10) years after disturbance.

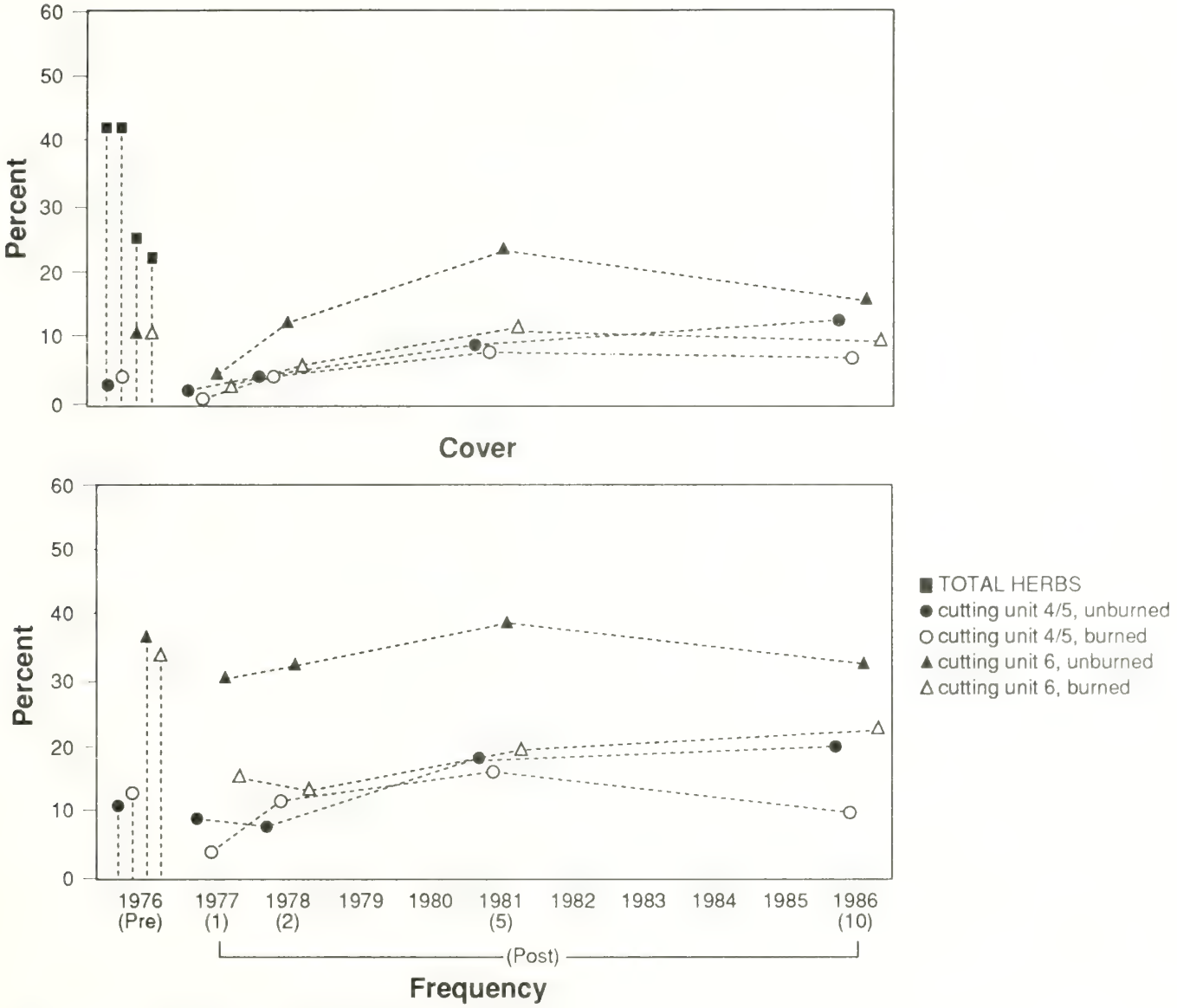

Figure 12—Cover (percent) and frequency (percent) of *Carex geyeri* in unburned and burned plots in cutting units 4/5 and 6 predisturbance (pre) and postdisturbance, (1), (2), (5), and (10) years after disturbance.

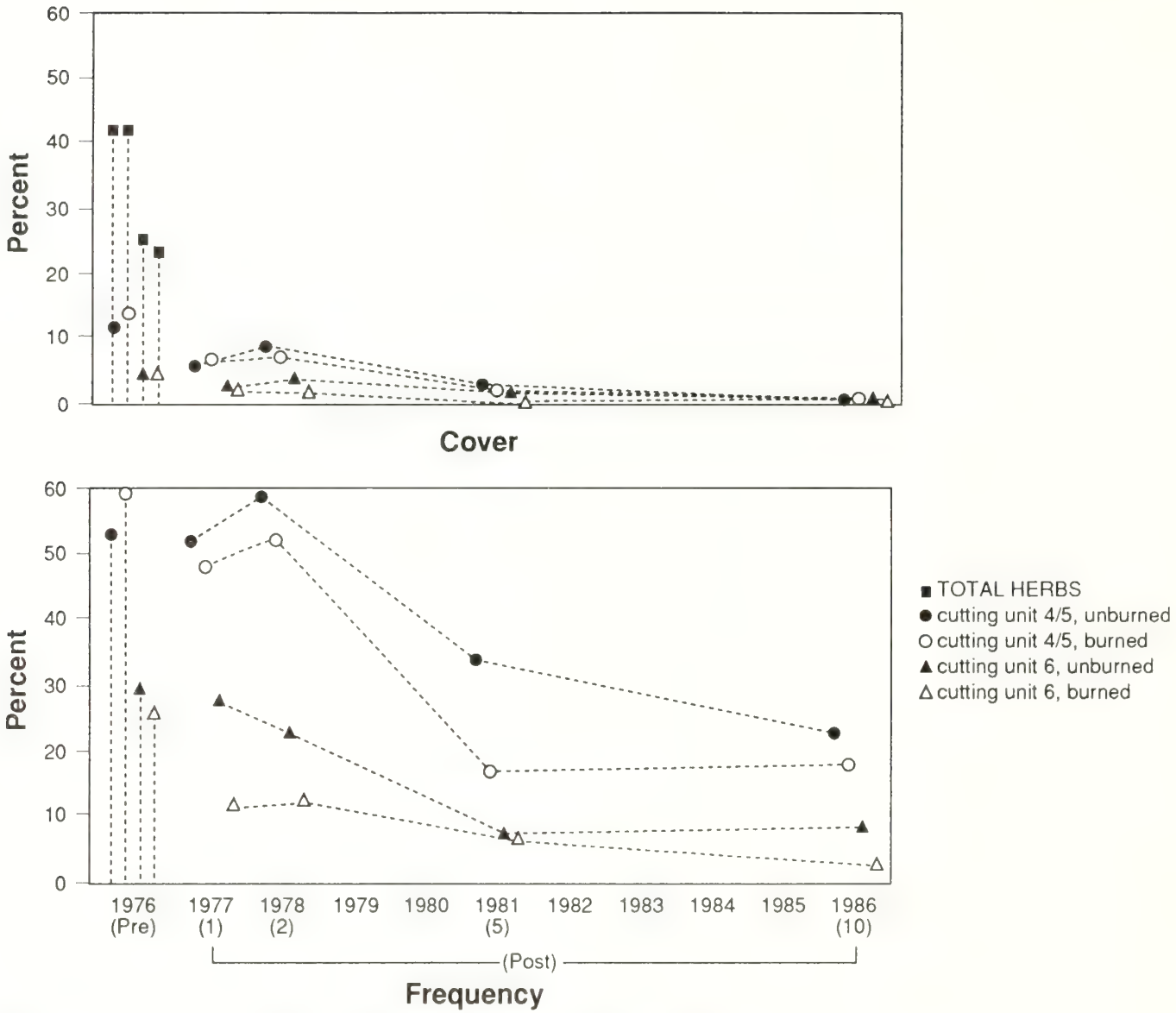

Figure 13—Cover (percent) and frequency (percent) of *Lathyrus nevadensis* in unburned and burned plots in cutting units 4/5 and 6 predisturbance (pre) and postdisturbance, (1), (2), (5), and (10) years after disturbance

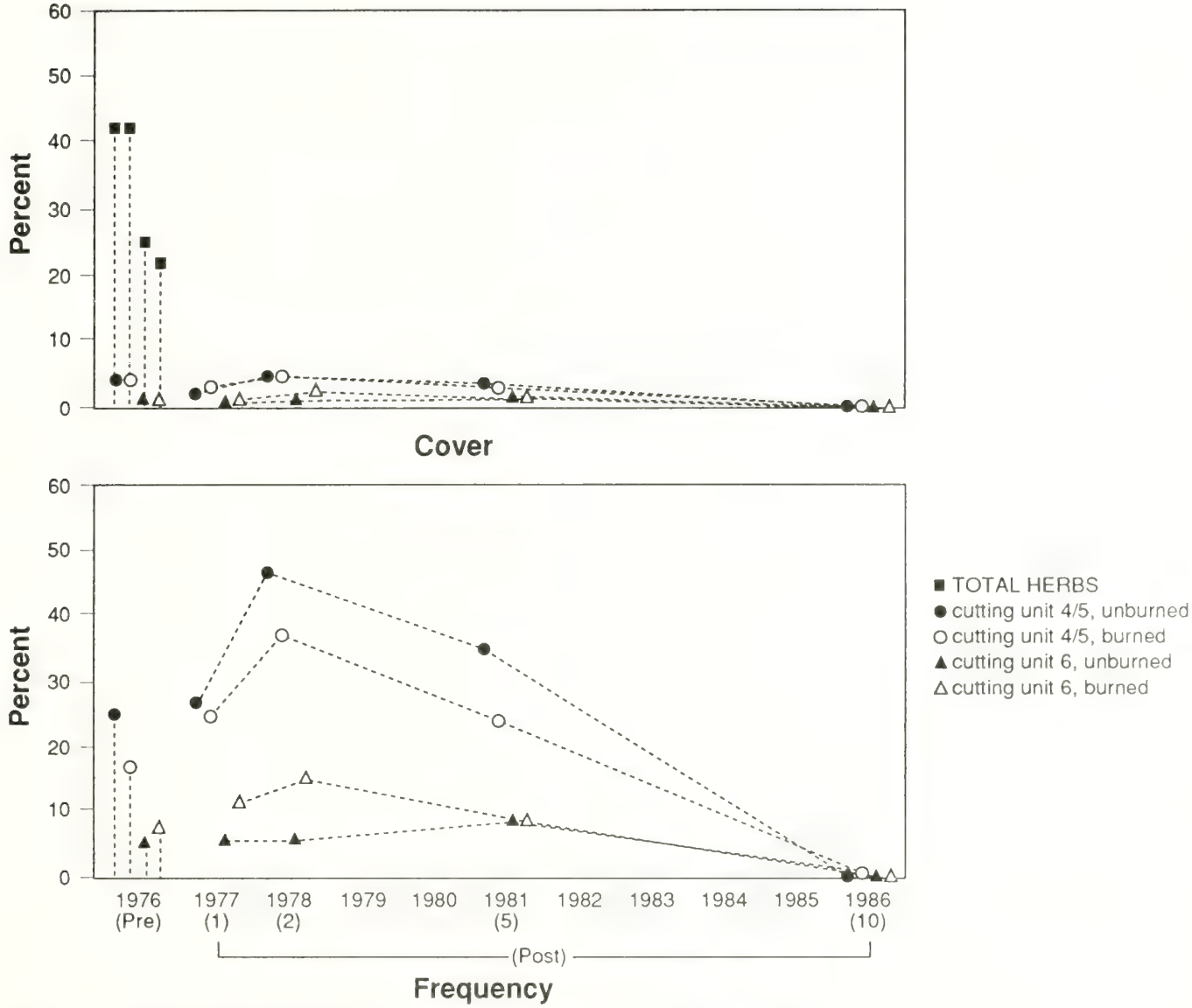

Figure 14—Cover (percent) and frequency (percent) of *Arnica cordifolia* in unburned and burned plots in cutting units 4/5 and 6 predisturbance (pre) and postdisturbance, (1), (2), (5), and (10) years after disturbance.

study area both before, and after the disturbance. The dominant forbs were *Lathyrus nevadensis* and *Arnica cordifolia*.

Many of the herbs, as with the shrubs, increased to year 5, then declined, though as with the shrubs, this was probably related to the weather conditions. Only *Lathyrus* and *Arnica* appear to have been affected by the treatment. Both peaked the second year following the disturbance, after which both cover and frequency declined. The sites may now be too exposed by the removal of the tree cover to maintain high coverages of these two herbs, both of which are often found in near climax communities.

Carex geyeri, like *Physocarpus*, may have been affected by the higher severity burning in cutting unit 6. In most cases, herbs responded similarly on burned and unburned plots in all cutting units. However, *Carex geyeri* on burned plots in cutting unit 6 was slower to reestablish. After 10 years, cover of *Carex* was only half the cover on unburned plots. Like *Physocarpus*, the *Carex* appears to have been affected by the more severe burning in cutting unit 6.

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Shrub frequency, cover, and height, and herb frequency and cover were measured on plots from two Douglas-fir habitat types in three cutting units. The plots were measured prior to helicopter yarding and broadcast burning and then 1, 2, 5, and 10 years later. The broadcast burning was more severe on one cutting unit than the other two. Vegetation was essentially the same on unburned and burned plots in the less severely burned cutting unit both before and after the treatment. However, the vegetation was altered on the more severely burned plots.

KEYWORDS: shrubs, herbs, frequency, cover, height.

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Predicting Timber Sale Costs From Sale Characteristics in the Intermountain West

Ervin G. Schuster
Michael J. Niccolucci

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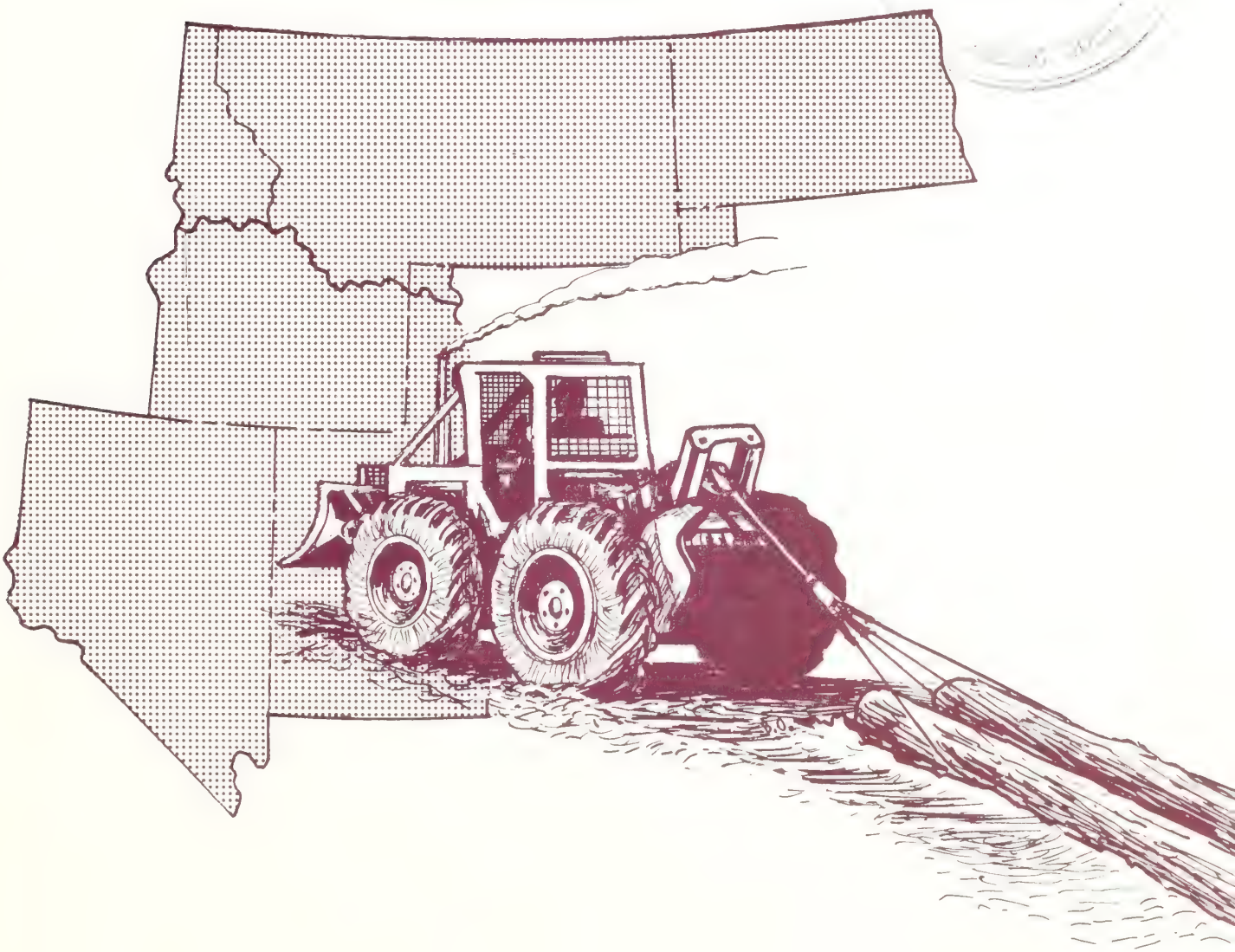

THE AUTHORS

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RESEARCH SUMMARY

Information about logging and roading costs can be very important to planning and designing timber sales. Such cost-related information is developed and maintained by the Forest Service, U.S. Department of Agriculture, through a voluminous system of complex handbooks and supplements. This paper presents a much simpler, equation-based method to estimate timber sale costs. We present several statistical models designed to estimate logging and roading cost allowances for timber sales in the Forest Service's Northern and Intermountain Regions. Data were obtained from a sample of timber sales from National Forests between 1983 and 1985. Cost equations follow major appraisal cost categories—slash costs, transportation costs, and so forth. Equations were estimated by a simultaneous equation technique known as Seemingly Unrelated Regression. Equations accounted for 35 percent to 91 percent, averaging 58 percent, of the variation in cost allowances. Use of models to estimate cost changes is illustrated.

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INTRODUCTION

Economic analysis of timber sale design often requires estimates of logging and roading costs, or how these costs might change given a proposed sale modification. This cost information is also important when assessing economic efficiency for groups of timber sales and associated road networks, where questions of timing and cost savings are central to the analysis. Timber sale costs are important, because as costs per unit of timber harvested go up, timber value per unit volume goes down.

Logging and roading costs are not directly incurred by the stumpage seller. Neither can they be directly observed. They are borne by and known to the timber purchaser only. The stumpage seller can only surmise what these costs are. In the Forest Service, U.S. Department of Agriculture, special studies are conducted of logging and roading costs. Purchaser records are inspected; time and motion analyses are performed. Findings are presented through a complex system of tables and charts in manuals, handbooks, and supplements. This information is widely used by the Forest Service and other organizations for various purposes, but primarily as the basis for cost allowances when timber stumpage is appraised by the "residual value" method (see Combes 1980).

Unfortunately, this cost information can be very cumbersome or time-consuming to access and can result in far more detailed data than are really necessary. In this paper we present an alternative approach to developing cost allowances. The following presents a set of equations that can be used to easily estimate logging and roading cost allowances. These estimates are suitable for use in economic analyses of individual or groups of timber sales wherever traditional cost allowances are used.

METHODS

The kinds of timber sale cost information needed to appraise timber (stumpage) value with the residual value (RV) method provide the framework for our modeling of cost allowances. A simplified depiction of RV-appraised stumpage value, treating the costs of permanent (specified) roads as a timber sale cost, is:

Total value (of the products made from the logs)
– Manufacturing cost allowance
– Logging cost allowance
– Roading cost allowance
– Profit and risk allowance
= Stumpage value (appraised)

In the case of the Forest Service, agency policy indicates that the appraised stumpage value will be based on an operator of average efficiency (USDA FS 1977). This means that cost allowances, product value specification, and so on are all geared to the "average" operator. But the highest (or winning) bidder may be of above-average efficiency. Depending on a number of factors (USDA FS 1987), the highest bid on the sale may exceed the appraised value by a "bid premium":

Stumpage value (appraised)
– Stumpage value (highest bid)
= Bid premium

Conceptually, bid premium can be related to the amount of competition for the sale and/or incorrect specification of total value or cost allowances, all relative to the winning bidder. If cost allowances are excessive compared to the winning bidder's actual costs, bid premium will be larger than when cost allowances are inadequate.

We developed five equations to predict timber sale cost allowances and another equation to predict bid premium:

Logging costs
  Stump-to-truck (fell, buck, skid, load) 1
  Transportation (haul, road maintenance) 2
  Slash 3
  Temporary roads 4
Roading costs (permanent roads) 5
Bid premium 6

Normally, we would use the traditional multiple linear regression to estimate each cost allowance equation. But costs in one phase of the timber sale can affect costs in another phase. For example, the method of felling and bucking can affect the ease of slash removal and/or the need for temporary roads. Hence, the costs and cost equations associated with these processes are not independent of each other. Under this circumstance, conventional estimates of the regression coefficients would be biased and inefficient (Kmenta 1971). This problem was overcome by using the technique of Seemingly Unrelated Regression (see Kmenta 1971), a technique wherein all coefficients in all equations are estimated simultaneously. Statistical tests were conducted at the 10 percent level.

Data were obtained from records of a random sample of 224 timber sales completed between 1983 and 1985 on National Forests in the Northern and Intermountain Regions of the Forest Service (fig. 1). These were large-volume sales, each containing 2 million bd ft or more.

Information about each sale was found in official sale records, such as the timber sale report and appraisal summary.

Cost allowances and bid premiums were used as dependent variables, both expressed in dollars per thousand board feet (M bd ft) of timber harvest. Detailed cost information, such as allowances for felling and bucking costs, slash disposal costs, and so on, was obtained directly from the timber sale appraisal summary (Forest Service Form 2400-17). Similarly, information from sale summary was used to calculate bid premium as the difference between advertised rate and high bid. All dollar information was expressed in 1985 dollars, using the GNP Implicit Price Deflator (BOC 1987).

Sale characteristics were used as the independent variables. Various timber sale records provided information on 40 sale characteristics, including sale *features* such as volume harvested and miles of road construction and sale *requirements* such as dust control and haul restrictions. Sale features were measured as continuous variables. Sale requirements were binary, measured as 0 or 1, present or absent.

Cost allowance equations were estimated in four steps. First, linear correlation analysis eliminated all but the 26 most promising or useful sale characteristics. Subsets from these 26 characteristics were used as potential independent variables to estimate each cost equation. Second, traditional multiple linear regression analysis was next used to identify the best subset of the 26 potential variables for each cost allowance model (see Draper and Smith 1981 on adjusted R^2 and Mallow's Cp). Third, using those variables, cost equations were reestimated with the Seemingly Unrelated Regression routine of SORITEC software (Sneed and others 1986). Finally, equations were tested for compliance with underlying statistical assumptions (see Weisberg 1980 on Box-Tidwell analysis) and two transformations adjusted for nonlinear relationships: the reciprocal transformation ($Y = 1/X$) and the square root transformation ($Y = X^{1/2}$). If any of the previously identified variables became nonsignificant in the reestimated equations, they were discarded and the equation again reestimated. Ultimately, 19 sale characteristics were used as independent variables; the rest were dropped from further consideration.

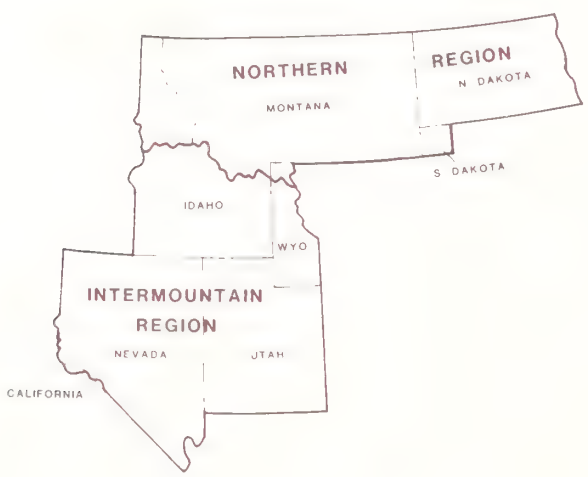

Figure 1—The Northern Region and Intermountain Region of the Forest Service.

Although bid premium depends on both market circumstances and errors in cost allowances, we were interested only in the cost allowance portion. It is quite difficult, however, to ascertain how much of the bid premium is due to cost allowance errors and how much to the effect of market circumstances. Our approach was therefore restrained, purposefully limiting the portion of bid premium ascribed to errors in cost allowance. The bid premium equation was estimated with traditional multiple linear regression through a three-step process. In the first step, bid premium was modeled as a function of market-related variables only—number of bidders and the selling price of lumber. This effectively ascribed the maximum amount of bid premium to market circumstances. In the second step, the five cost categories were added as independent variables to that model, and the model reestimated. Statistically nonsignificant cost categories were discarded, and the model was again reestimated in the third step. Coefficients on cost category variables depict the influence of cost allowance errors on bid premium.

RESULTS

In total, 12 equations were estimated—six (the five cost categories plus the bid premium equation) for the Northern Region and six for the Intermountain Region. The listing below shows that allowances for stump-to-truck costs were most important, accounting for more than half of the $153/M bd ft overall averages in allowances:

	Northern and Intermountain Regions average allowance *1985 $/M bd ft*
Stump to truck	$82.15
Transportation	38.54
Slash	13.59
Specified roads	18.13
Temporary roads	.97
	$153.38
Bid premium	–26.39
	$126.99

These cost allowances combine with overbids to account for total adjustments. The variation in the cost allowances explained by the equations ranged from 35 percent to 91 percent, averaging 58 percent. Equations for the Intermountain Region were above the average, the Northern Region below.

The 19 variables used in final models are defined in table 1. All but one described sale characteristics; the sole sale requirement variable concerned dust control. As

indicated before, measurements on these variables for each sale were made from sale records. For example, required corridor spacing (SPACE), measured in feet, is specified in both the contractual clauses of the sale contract and the timber sale report.

Not to be confused with total costs, the following equations express costs in thousand board feet of timber harvested, a type of average cost. All values are expresssed in 1985 dollars.

Stump to Truck

Stump-to-truck costs include costs associated with felling and bucking trees as well as skidding trees to the landing and loading. These costs were the largest, accounting for over half of the allowances modeled. Stump-to-truck cost allowances averaged $85.02/M bd ft in the Northern Region and $76.82 in the Intermountain Region.

Table 2 shows the final cost estimation models for the Regions studied along with the percentage of variation in

Table 1—Independent variables used in study

Variable	Description	Units
	Sale Characteristics	
SPLT	Selling price, lumber tally	$ per M bd ft (Scribner)
VOL	Total sale volume harvested	M bd ft (Scribner)
VPA	Volume per acre harvested	M bd ft (Scribner)
ACRES	Acres harvested in sale	Acres
%TRA	Percent volume tractor yarded	Percent
SPACE	Corridor spacing	Feet
%GSL	Percent volume group selection	Percent
%CC	Percent volume clearcut, seedtree, or right-of-way	Percent
STEEP	Sale area > 55 percent slope	Acres
FLAT	Sale area 0-35 percent slope	Acres
#UNIT	Number of cutting units	Number
YT	Average maximum tractor yarding	Feet
UHAUL	Unpaved haul distance	Miles
PHAUL	Paved haul distance	Miles
ADBH	Average tree diameter	Inches
TEMP	Temporary road construction	Miles
NEW	New road construction	Miles
RECON	Old road reconstruction	Miles
	Sale Requirements	
DUSTR	Dust control restrictions	1 = Yes 0 = No

Table 2—Stump-to-truck cost estimation equations[1]

	Northern Region		Intermountain Region	
Variable	Coefficient	Standard error	Coefficient	Standard error
Constant	26.32	5.60	112.14	17.64
%TRA	–.33	.05	–1.00	.11
$VPA^{1/2}$			–6.35	2.53
1/VPA	140.40	40.17		
#UNITS			.28	12
YT			.03	.01
1/ADBH	760.00	83.82	871.49	119.41
$FLAT^{1/2}$			–.70	.24
SPACE			–.08	.03
STEEP	.10	.02		
%GSL	.48	.11		
$ACRES^2$	1.32×10^{-5}	$.44 \times 10^{-5}$		
R^2		.68		.65

[1]See table 7 for possible adjustment.

stump-to-truck costs explained by the models (labeled "R^2"). Both models performed exceedingly well. The model developed for the Northern Region explained 68 percent of the variation in stump-to-truck costs. The Intermountain Region model explained 65 percent of the variation. Tree size (ADBH) and the amount of steep land (STEEP) were the most important variables explaining stump-to-truck costs in the Northern Region. Percent of the volume tractor yarded (%TRA) and ADBH were most important in the Intermountain Region.

In effect, the equations portray stump-to-truck costs as a function of terrain, slope, and tree size. STEEP and the amount of flat land (FLAT) obviously relate to slope. But so does %TRA, because tractor operations typically take place on flatter lands. Steepness is costly, shown by the positive sign on the coefficients. As the percentage of the timber sale tractor yarded goes down or steep land goes up, stump-to-truck costs go up. The ADBH variable indicates that regardless of slope, it is less costly (per thousand board feet) to log larger trees.

Transportation

Transportation costs could also be called log haul costs. The term refers to the costs of moving logs from the timber sale to the initial milling site—haul costs and road maintenance costs. These costs averaged $36.10/M bd ft in the Northern Region and $42.99 in the Intermountain Region.

Cost estimation models developed for transportation costs explained the most variation of any cost model developed. The equation shown in table 3 for the Northern Region accounts for 76 percent of the variation, while the Intermountain Region model accounts for 91 percent. In both Regions, miles of unpaved haul road (UHAUL) was the single most important variable, accounting for about half of the variation explained. Along with unpaved haul, paved haul (PHAUL) and log size (ADBH) were consistently important, in that order.

The cost equations explain transportation costs by distance traveled. For both Regions, the distance of unpaved and paved haul are significant variables. Together, they sum to total haul distance. These variables always have positive coefficients, meaning that as distance increases so do transportation costs. The size of the coefficients suggests that each mile of unpaved haul is about twice as costly as paved haul. The ADBH variable shows that, regardless of distance, it is less costly (per thousand board feet) to haul large logs than small ones. Apparently, this reflects the notion that smaller logs have less board-foot volume per unit of log weight than larger logs. Because dust control restrictions (DUSTR) is a binary (0/1) variable, transportation costs in the Northern Region increase by $4.92/M bd ft when it is present.

Slash

Slash disposal costs refer to costs of cleaning up logging debris to prepare the site for regeneration activities. Slash disposal costs averaged $14.44/M bd ft in the Northern Region and $12.00 in the Intermountain Region.

The relatively low R^2's shown in table 4 for the slash cost models suggest that slash cost allowances were more variable than other costs discussed. Only about half of the variation in slash costs allowances was explained by these models. Moreover, the importance of variables differed widely between Regions. Corridor spacing (SPACE) was the single most important explanatory variable in the Northern Region, while volume per acre (VPA) was most important in the Intermountain Region. VPA and the number of cutting units (#UNITS) were second important in the Northern Region and percent of the area clearcut (%CC) was second in the Intermountain Region.

The cost equations portray slash costs in terms of ease and efficiency of operation. Narrower corridor spacing, flatter ground, and either more group selection or less clearcut all make for easier operations and lower unit costs. Similarly, greater volumes per acre and fewer cutting units both promote efficiency, and hence cost economies of scale in slash removal operations. But so does removing slash from larger diameter trees, because sites with these trees will carry a disproportionately large volume per unit of land.

Permanent Roads

In the Forest Service, these permanent roads are called "specified" roads. They are major roads that access the timber sale and will remain after the sale is completed. These roads can become part of an official, numbered road network for a National Forest. The average cost of permanent roads was $19.62/M bd ft in the Northern Region and $15.93/M bd ft in the Intermountain Region.

The cost estimation models developed for permanent roads explained about 35 and 55 percent of the variation in costs in the Northern Region and Intermountain Region, respectively. Table 5 shows these models. The miles of new roads to be constructed (NEW) was clearly the most important variable in explaining permanent road costs. It alone accounted for about half of the variation explained. Note that total road construction is simply the sum of new road miles and reconstructed road miles.

Cost equations for permanent roads show that miles of road constructed are useful in predicting road costs per thousand board feet. Assume that in addition to fixed costs, the cost per mile of road constructed is constant. The road coefficients identified in this study then imply that the amount of timber accessed by new roads increases faster than do the miles of access roads, on a percentage basis. For under these circumstances, permanent road costs, expressed in terms of a unit of timber harvest, increase as a decreasing function of miles of access roads.

Table 3—Transportation cost estimation equations[1]

Variable	Northern Region		Intermountain Region	
	Coefficient	Standard error	Coefficient	Standard error
Constant	–7.96	3.75	–8.93	2.42
1/ADBH	225.61	35.04	322.43	28.56
UHAUL	.98	.05	1.01	.04
PHAUL	.44	.05	.50	.03
DUSTR	4.92	1.65		
R^2		.76		.91

[1]See table 7 for possible adjustment.

Table 4—Slash cost estimation equations

Variable	Northern Region		Intermountain Region	
	Coefficient	Standard error	Coefficient	Standard error
Constant	11.59	2.83	4.53	3.52
SPACE	.05	.01	.02	.01
VPA			–.48	.11
1/VPA	77.47	16.38		
ADBH	–.48	.16		
1/ADBH			149.80	41.31
FLAT	–.01	0	–.002	.001
%CC			.04	.02
%GSL	–.11	.05		
#UNITS	.27	06		
R^2		.42		.50

Table 5—Permanent road cost estimation equations

Variable	Northern Region		Intermountain Region	
	Coefficient	Standard error	Coefficient	Standard error
Constant	2.84	2.13	–9.72	3.20
STEEP			.03	.01
NEW$^{1/2}$	8.12	1.05	9.20	1.15
RECON$^{1/2}$	2.93	1.10	4.10	1.09
1/VOL			31,321.00	8,516.00
R^2		.35		.55

Temporary Roads

Unlike permanent roads that remain after the timber sale is finished, temporary roads return to nature. Road access is blocked, the roadbed is planted to grass, and so on. Temporary roads are typically minor facilities within the timber sale and are relatively inexpensive. The average cost of temporary roads in the Northern Region was $0.85/M bd ft and $1.19/M bd ft in the Intermountain Region.

Table 6 presents the models developed for temporary road costs. As shown by the R^2's, these models explain about the same amount of variation in costs as previously shown for permanent roads. And again, the model for the Intermountain Region explained more variation in temporary road costs than did the Northern Region's model—56 percent vs. 38 percent. In both Regions, the miles of temporary roads (TEMP) was by far the most significant explanatory variable. In the Northern Region, sale size (ACRES) was next most important, while in the Intermountain Region, total sale volume (VOL) was second.

Temporary road costs (per thousand board feet) are best predicted from knowledge of road miles. Given the sizes of the timber sales studied, temporary road costs per unit of timber harvested increase as a function of miles of roads. Stated differently, timber sales with more miles of temporary road do not have correspondingly more volumes harvested. The sale size variable (in acres) in the Northern Region and the sale volume variable (in million board feet) in the Intermountain Region both represent sale size, and both reflect cost economies of scale.

Bid Premium

To this point our cost estimation models merely predict cost allowances developed by Forest Service personnel when appraising timber under the residual value method. Nobody really knows if these cost allowances are correct. Similarly, nobody really knows if the product values described in the appraisal are correct. If cost allowances are too high and/or value allowances too low, the winning stumpage bid may well exceed the appraised value, especially if several bidders are competing for the sale. This differential is "bid premium," sometimes called "overbid." Bid premium averaged about $36.16/M bd ft in the Northern Region and $8.60/M bd ft in the Intermountain Region.

Table 7 shows the models developed to estimate bid premium. As stated earlier, these models attempt to account for errors in product value (through SPLT), bidder competition for the sale (through #BIDDERS) and errors in cost allowances (through five cost categories). Final models explained about 55 percent of the variation in bid premium in the Northern Region and only 19 percent in the Intermountain Region. The amount of variation explained by the Intermountain Region model is surprisingly low, indicating that our simple model is not adequate to explain bid premium. Perhaps unmodeled factors, such as those related to purchaser expectations and speculation, play a more dominant role in the Intermountain Region than in the Northern Region.

Table 6—Temporary road cost estimation equations

	Northern Region		Intermountain Region	
Variable	Coefficient	Standard error	Coefficient	Standard error
Constant	0.63	0.17	2.82	0.51
TEMP	.56	.06		
$TEMP^{1/2}$			1.65	.19
$VOL^{1/2}$			−.04	.01
ACRES	−.0004	0		
R^2	.38		.56	

Table 7—Bid premium cost estimation equations

	Northern Region		Intermountain Region	
Variable	Coefficient	Standard error	Coefficient	Standard error
Constant	−17.85	9.55	−16.09	9.60
#BIDDERS	9.91	1.02	5.61	2.04
SPLT	.16	.02	.06	.03
Stump-to-truck	−.14	.08	−.11	.06
Transportation	ns[1]	ns	18	.11
Slash	ns	ns	ns	ns
Permanent road	ns	ns	ns	ns
Temporary road	ns	ns	ns	ns
R^2	.55		.19	

[1]ns = nonsignificant.

Statistically significant coefficients for cost categories mean that bid premium is systematically related to cost allowances. A negative coefficient means that bid premium is lowered because of this variable, implying that the appraisal's cost allowance was too small. When this situation occurs, cost estimates from previous equations should be increased. A positive sign means the cost allowance was too large; previous cost estimates should be decreased. Because cost category variables were measured in dollars per thousand board feet, coefficients are interpreted as a percentage adjustment.

Most of the variation in bid premium explained by our models used variables reflecting competition and product value—#BIDDERS and SPLT—not cost allowance variables. In fact, the #BIDDERS alone explained 53 percent (out of 55 percent) of the variation in bid premium in the Northern Region and 13 percent (out of 19 percent) in the Intermountain Region.

We therefore conclude that the cost allowance estimation equations previously shown are mostly adequate, as is, with three exceptions. In the Northern Region, the –0.14 coefficient on stump-to-truck cost estimates is statistically significant, implying that these cost estimates are about 14 percent too low. Similarly, significant coefficients for the Intermountain Region imply that stump-to-truck cost allowances there are about 11 percent too low while transportation cost allowances are 18 percent too high. Under these circumstances, estimated cost allowances should be adjusted if a better approximation of actual costs is desired. For example, an estimated transportation cost allowance of $50/M bd ft for the Intermountain Region should be decreased by 18 percent to $41 if an estimate of actual transportation cost is desired.

DISCUSSION

How well do the equations presented here actually model logging and roading costs, and for how long? We do not and cannot know how well our models of appraisal allowances estimate actual costs, because actual cost information is proprietary—known only to the logging operators. The only question to which we can respond is one of how well our cost allowance equations predict actual cost allowances. We think they perform quite well, explaining up to 91 percent of the variation in line item cost allowances. But technological change will cause our models to become out of date in the same way as the cost allowance manuals become out of date. We do not know when this will happen.

Figure 2 provides another perspective on how well our predicted cost allowances match actual allowances. The histograms show the percentage of predicted allowances within $10/M bd ft of the actual, within $10 to $20 of the actual, and within $20 to $30 of the actual. For example, 63 percent of the predicted transportation cost allowances (from our models) were within 10 percent of the actual allowance in the Northern Region; 76 percent of the predictions were within 10 percent of the actuals in the Intermountain Region. Because the average transportation cost allowance in the Intermountain Region was $42.99/M bd ft, that means more than three-fourths of the estimated transportation allowances were within $4.30 of the actual allowance. Overall, 78 percent of all estimates were within 30 percent of the means in the Northern Region; 71 percent were within 30 percent in the Intermountain Region.

We conclude with an illustration in which we estimate a *t*ransportation cost *a*llowance for a hypothetical timber sale from the *I*ntermountain *R*egion $(TCA)^{IR}$. For simplicity, assume this sale can be depicted as the mean value for each sale characteristic found important in this study. Those means are displayed in table 8. Table 3 earlier showed that transportation costs could be modeled as:

$$(TCA)^{IR} = -8.93 + 322.43(1/ADBH) + 1.01(UHAUL) + 0.50(PHAUL)$$

Table 8 shows the average diameter of the trees harvested (ADBH = 13.99 inches), along with the average miles of paved and unpaved roads. Using these averages, the allowance is calculated:

$$\begin{aligned}(TCA)^{IR} &= -8.93 + 322.43(1/13.99) + 1.01(12.27) \\ &\quad + 0.50(26.56) \\ &= -8.93 + 2.41 + 12.39 + 13.28 \\ &= \$39.79/M \text{ bd ft}\end{aligned}$$

This is only about 7 percent off the actual average transportation allowance, $42.99/M bd ft.

The question of bid premium must also be considered. However, adjustments reflecting the effect of errors in cost allowances on bid premium should not always be made. We recommend that if the appraisal's objective is to estimate or approximate Forest Service cost allowances, no adjustment should be made. But if the objective is to estimate actual logging and roading costs (or to estimate stumpage value where cost allowances are not combined with an independent estimate of bid premium), apply the cost allowance adjustments shown in table 7. Finally, if the objective is to estimate stumpage value where cost allowances are combined with an independent estimate of bid premium, cost allowances should not be adjusted; this will preclude the possibility of double counting the effect of bid premium.

Assume the adjustment is appropriate. Then the transportation cost coefficient of 0.18 shown in table 7 means that the transportation allowance is 18 percent too high. Therefore, a more accurate portrayal of these costs would be to lower the transportation cost allowance to $32.63/M bd ft (= 39.79(1.0 – 0.18)).

If the cost allowance displayed in 1985 dollars is not desired, simply convert the allowance to the desired base year. The following tabulation shows a listing of conversion factors:

Factors to convert to new base year

Year	Multiplication factor
1980	0.7707
1981	.8453
1982	.8993
1983	.9344
1984	.9721
1985	1.0000
1986	1.0261
1987	1.0567

Source: Adapted from BOC 1987 and BEA 1988.

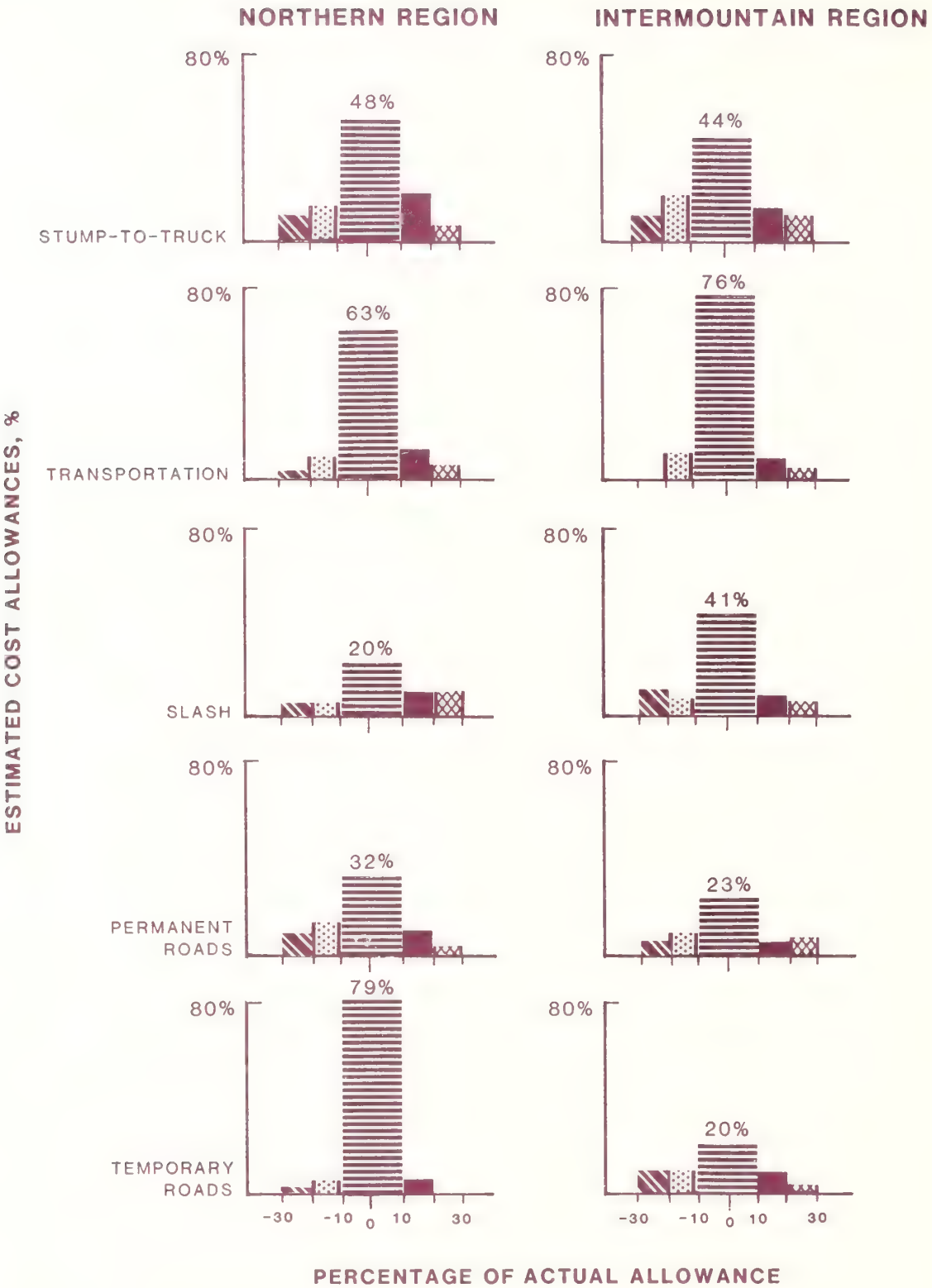

Figure 2—Closeness of cost allowance predictions to cost allowance, by cost category, for Northern Region and Intermountain Region

Table 8—Means of independent variables used in study

Variable	Units	Northern Region	Intermountain Region
	Sale Characteristics		
SPLT	$ per M bd ft	220.05	235.45
VOL	M bd ft	8,243.63	8,220.35
VPA	M bd ft	20.37	10.28
ACRES	Acres	404.77	800.03
%TRA	Percent	56.93	86.69
SPACE	Feet	56.64	56.32
%GSL	Percent	2.80	4.03
%CC	Percent	69.70	46.31
STEEP	Acres	47.50	50.40
FLAT	Acres	236.33	582.83
#UNITS	Number	17.35	21.80
YT	Feet	672.26	659.29
UHAUL	Miles	13.93	12.27
PHAUL	Miles	20.59	26.56
ADBH	Inches	13.66	13.99
TEMP	Miles	1.06	1.44
NEW	Miles	3.54	2.56
RECON	Miles	1.87	1.92
	Sale Requirements		
DUSTR	1 = Yes 0 = No	0.79	0.82

These factors can be applied to any dollar-based number presented in this paper, including means, coefficients, or results such as the $32.63/M bd ft transportation cost estimate just calculated. Assume this value is desired in 1987 dollars. Simply locate the conversion factor for 1987 shown in the above tabulation (i.e., 1.0567). The converted value ($34.48) is determined by multiplying the value in question by the conversion factor (= 32.63 x 1.0567).

Finally, as with all research, results presented in this paper should not be applied to situations differing appreciably from those contained in the timber sales studied. The set of means shown in table 8 shows the magnitude of many sale characteristics. More importantly, sales sampled included only sales of 2 million bd ft or more. Therefore, study results should not be applied to smaller volume sales. Within these limitations, equations presented for cost allowances can serve many uses, especially in analyses related to timber sale planning and design.

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Schuster, Ervin G.; Niccolucci, Michael J. 1989. Predicting timber sale costs from sale characteristics in the Intermountain West. Res. Pap. INT-406. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 9 p.

Presents a simple, equation-based method to estimate timber sale costs. Data were obtained from timber sales on National Forests in the Intermountain West. Equations were estimated by Seemingly Unrelated Regression.

KEYWORDS: timber management, logging costs, stumpage value, timber sales

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**Intermountain
Research Station**

Research Paper
INT-407

July 1989

Characteristics of Long Vertical DC Arc Discharges

Don J. Latham

THE AUTHOR

DON J. LATHAM received his bachelor's degree in physics from Pomona College in 1960, and his master's in 1964 and Ph. D. in 1967, both in earth science, from the New Mexico Institute of Mining and Technology. From 1968 to 1976 he taught and did research in atmospheric electricity in the Rosenstiel School of Marine and Atmospheric Science, University of Miami. In 1976 he joined the Intermountain Research Station's Intermountain Fire Sciences Laboratory (formerly Northern Forest Fire Laboratory), in Missoula, MT, as a research meterologist/physicist.

RESEARCH SUMMARY

Vertical electric arc discharges of varying lengths to a maximum of 10 cm were drawn between carbon electrodes. The arcs were powered by a bank of 40 series-connected lead-acid batteries, with a Silicon-controlled-rectifier switch for accurate timing. Initiation of the arc was accomplished by three methods, two using tungsten wire and one a moving carbon electrode. Current was limited by a series resistance made of carbon rods.

Current in the circuit and voltage across the arc were measured for several values of current and electrode spacing. The measurements showed that the voltage drop across the arc is independent of current and dependent only on electrode spacing, and did not depend on how the arc was initiated. The current in the arc, on the other hand, was independent of the arc spacing and initiation method and depended only on the source resistance and source voltage, or, equivalently, on the current in the circuit if the arc was replaced with zero resistance.

Observations were made of some arcs with a 1,000-frame-per-second video system. The results showed the presence in all arcs of a cathode and an anode jet. The jets did not meet in an organized fashion, but behaved rather as two streams of water might. The anode jet wandered around the cathode jet, which was very nearly stationary. There seems to be a balance between minimum resistance, that is a hot gas column in a straight line between the electrodes, and the instability of two hot gas jets meeting colinearly in opposite directions. Due to time and data constraints, this system was analyzed in qualitative terms.

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Characteristics of Long Vertical DC Arc Discharges

Don J. Latham

INTRODUCTION

This paper contains observations of the operating characteristics and behavior of a vertical dc arc ignition source. The construction of the source is given in Latham (1987). The arc system was made to obtain ignition probabilities for wildland fine fuels subjected to electrically generated ignition sources such as lightning or downed powerlines. A simplified diagram of the system appears as figure 1.

The arc is generated by switching a 500-v (nominal) source in series with a resistance across a 9-cm (nominal) gap between two carbon rod electrodes. The gap is initially shorted by a 0.1-mm-diameter tungsten wire. The wire, upon initiation of current flow, heats and then burns, creating an ionized medium in which the arc forms. At the end of the desired time interval, the voltage source is interrupted, leaving a hot gas channel that decays to ambient temperature through radiation and diffusion (Latham 1986). In use, typical fuels are arranged around the wire and are then heated by the arc. Arc current and duration, together with fuel state parameters, were varied to obtain ignition probabilities. A later adaptation of the device used a moving electrode to strike the arc, but the basic testing procedure remained the same.

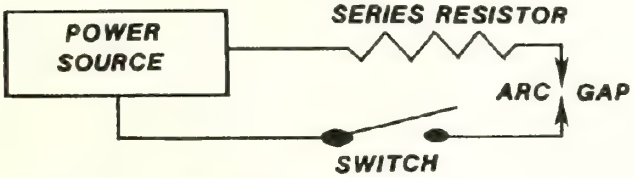


Figure 1—A simplified arc electrical circuit diagram.

Figure 2 is an example of an actual record of current and voltage traces for an arc generated by the system. Portions of the arc time behavior are labeled in the caption. The initial current onset is called the starting transient (1). Following that is the wire heating and ionizing portion (2), then the arc striking time (3), the main arc, or arc proper (4), and the stopping transient (5).

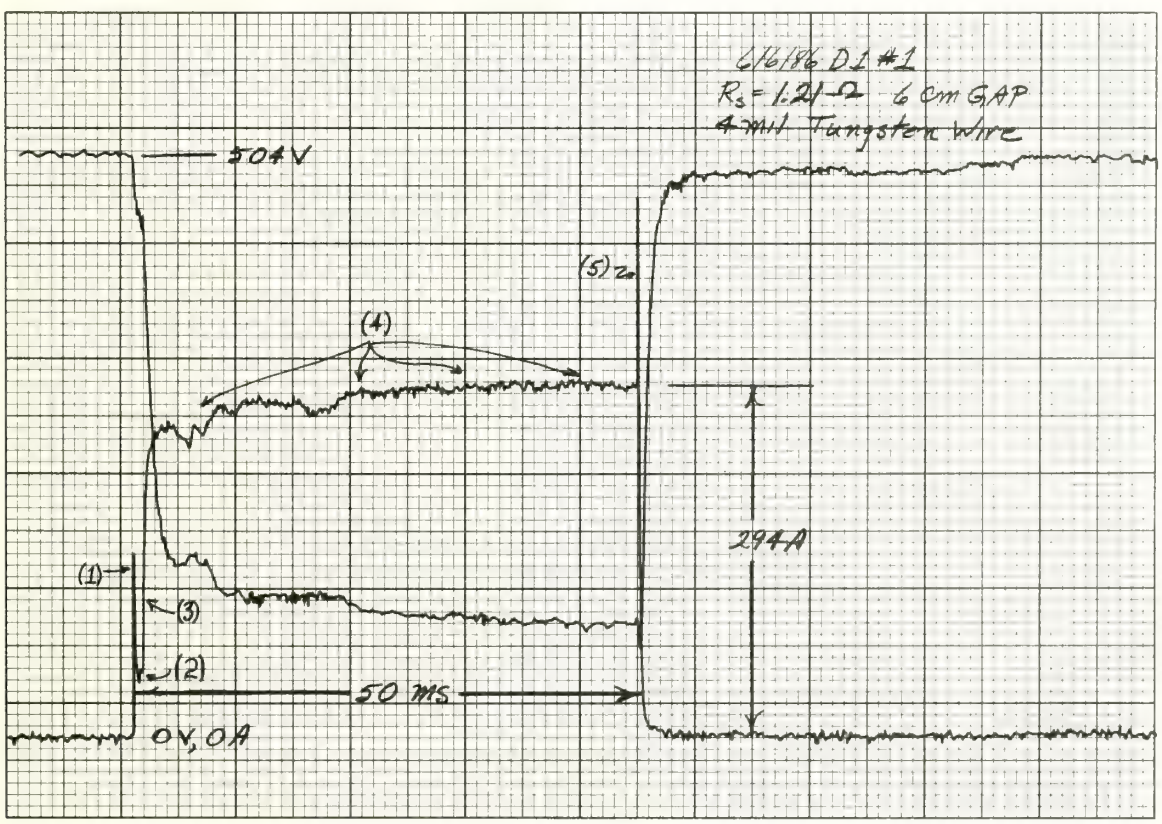


Figure 2—Current and voltage behavior with time for a typical arc in this study. Arc behavior segments are indicated: (1) starting transient, (2) wire heating and ionizing, (3) arc striking, (4) main arc duration, and (5) stopping transient.

The measurement of the gross characteristics of the arc, that is, the way the current in the arc and the voltage drop across it vary with gap length and source conductance was the main emphasis of the phase of the study reported here. We found that the voltage drop increased with gap length in a regular way. For a fixed gap length, and increasing short-circuit current, the arc current increased. The arc voltage drop, in other words, depends almost entirely on the arc length, and the arc current almost entirely on the source short-circuit current, as the model (Latham 1986) predicts.

Arc behavior was recorded with a 1000-image-per-second video camera. The flow patterns in the arc seem to be dominated by a jet from the anode and one from the cathode. The meeting of these two jets is not stable, yet the arc, considered as an electrical circuit element, is stable, as the current measurements show clearly.

The results of these investigations did show that the arc was suitable for the purpose of obtaining probability of fuel ignition.

INSTRUMENTATION

Construction details of the arc electric circuit measuring devices are given in Latham (1987). Briefly, the current in the circuit is measured with a Hall effect device, the voltage across the arc gap or series resistor with a calibrated resistive divider and isolation amplifier, and arc luminosity with an Si detector. The current and voltage devices are calibrated to 1 percent, but due to well-known difficulties with radiation measurements, the luminosity measurement is relative from event to event, and serves as a qualitative indicator only. No luminosity was evident in the source characteristic observations. Data were recorded on a Nicolet two-channel sampling oscilloscope with 12-bit precision and floppy disk storage. This recording technique enabled easy data recovery and precise measurement of timing and amplitude. Except for possibly missing very fast transients, errors due to data storage and retrieval can be considered negligible. A typical measurement taken with a shorted arc is shown in figure 3.

Figure 4 shows the result of an analysis of 53 cases in which the conductance was varied and the short-circuit current measured. Because the voltage source is made up of lead-acid batteries, the source voltage is a function of the current drawn, as the figure shows. The variability apparent in the figure is due to the large number of electrical contacts in the system, and cannot be avoided. Part of the variability is also due to the differing state of charge and temperature of the batteries. These factors necessitate measurement of voltage across the arc and also the current in the arc circuit during operation.

Discussion of the calibration of the current sensor will also provide insight as to the effect of resistance temperature variation and source variability. The calibration procedure was as follows: the arc gap was shorted, as previously described. The isolated voltmeter, separately

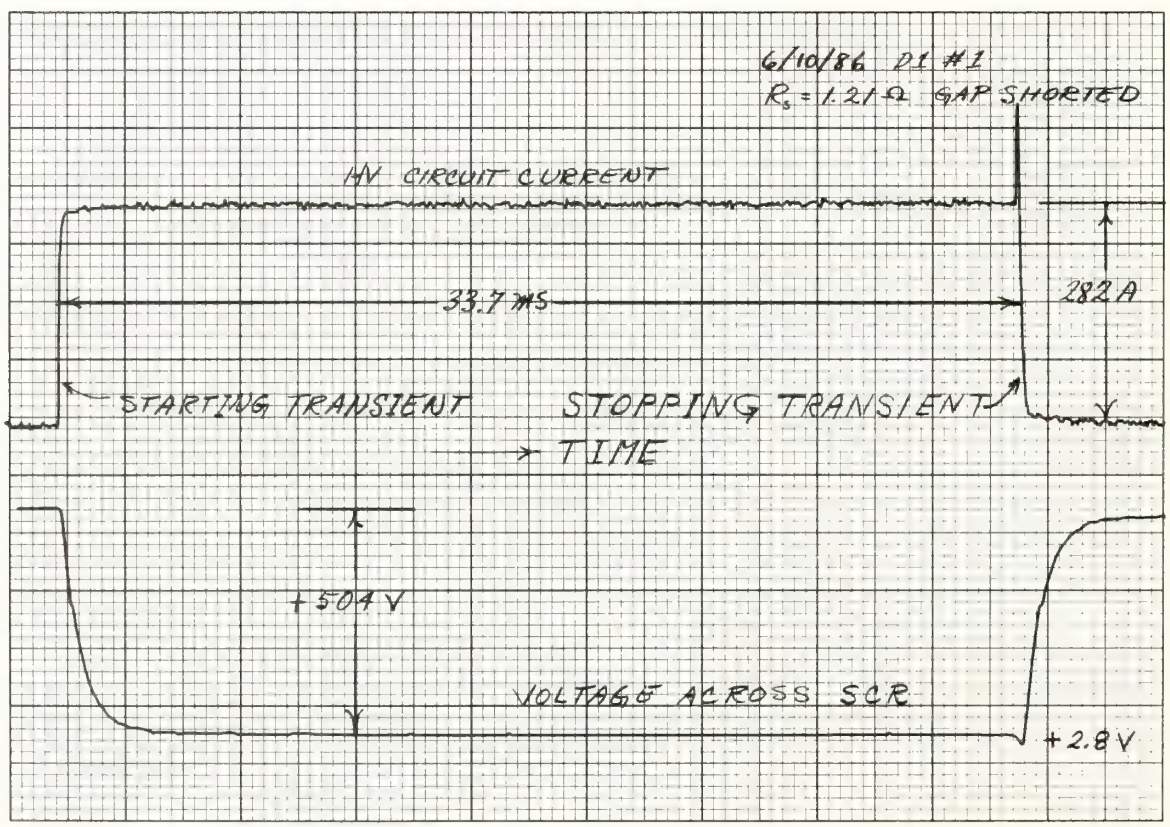
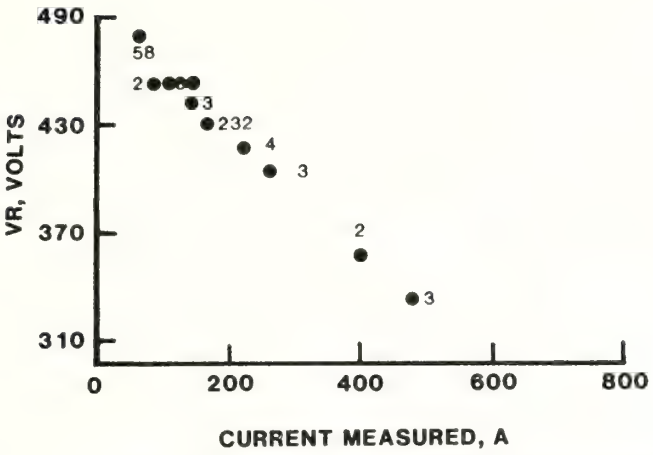


Figure 3—Current and voltage behavior for the system with the arc gap electrically shorted.

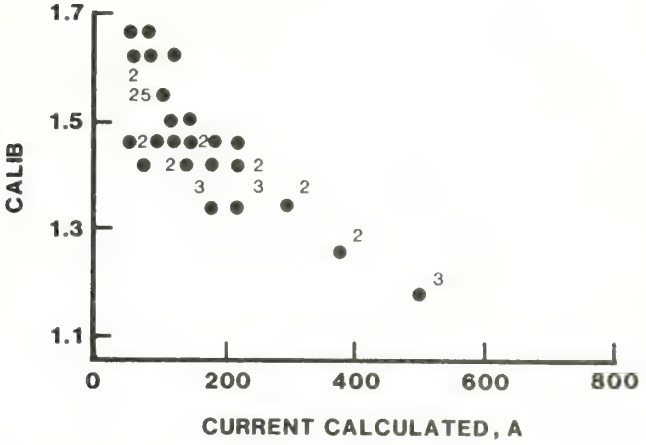


Unweighted least squares linear regression of VR

Predictor variables	Coefficient	Std error	Student's T	P
Constant	486.29	1.2896	377.08	0.0000
Curmeas	−3.0232E-01	5.7009E-03	−53.03	.0000

Cases included	53	Missing cases	0
Degrees of freedom	51		
Overall F	2.812E+03	P value	0.0000
Adjusted R^2	0.9818		
R^2	0.9822		
Resid. mean square	27.87		

Figure 4—A plot of voltage drop across the series resistor (in volts) vs. measured circuit current (in amperes). The results of a linear regression analysis are included.



Unweighted least squares linear regression of calib

Predictor variables	Coefficient	Std error	Student's T	P
Constant	1.5886	1.3024E-02	121.97	0.0000
Curcalc	−7.6517E-04	5.7244E-05	−13.37	0.0000

Cases included	53	Missing cases	0
Degrees of freedom	51		
Overall F	178.7	P value	0.0000
Adjusted R^2	0.7736		
R^2	0.7779		
Resid. mean square	2.911E-03		

Figure 5—Magnetic field device calibration factor (dimensionless) vs. calculated current (in amperes) in the arc circuit. A linear regression analysis is included.

calibrated against a digital voltmeter ($4\frac{1}{2}$ digits precision) was connected across the carbon rod resistor. The cold resistance of the rod was measured with a Wheatstone bridge (5-digit accuracy) and the circuit energized. The voltage and current were measured with the digitizing oscilloscope (12-bit precision). This procedure was carried out with varying cold resistances, with 53 data points taken.

The calibration factor for the current device is obtained by dividing the measured millivolt value into a current calculated from the measured voltage and cold resistance. The results are given in figure 5. If the resistance of the rod resistor were constant, the value of this calibration ratio would show a random scatter about some mean value. Instead, we found a steady decrease in the calibration value with increasing current. This decrease is due to the resistor having a value different from the cold value. As the current increases, the resistance decreases. Systematic variations in the calibration factor CALIB of figure 5 are due only to changes in the resistance produced by heating. The calibration factor is the zero-current value, or the constant in a linear regression (fig. 5). This calibration value is 1.59 a/mv.

SOURCE CHARACTERISTICS

Source characteristics, the current carrying capacity of the voltage and series resistance of figure 1, and the behavior of the SCR switching circuit were obtained by measuring current and voltage with a shorted gap and varying the source resistance. Time details of typical current and voltage measurements for the shorted gap are shown in figures 3 and 6 through 9. Figure 3 contains some nomenclature information as well. Note the portions of the records labeled starting transient and stopping transient; details of these are given in figures 7, 8, and 9. Also shown clearly in figure 3 is the poor time response of the voltage isolation amplifier, causing problems with the interpretation of fast-occurring details of the source and arc observations.

There is nothing remarkable about the current structure with respect to time in the shorted gap case. There is a small rise in the current during the short pulse of figure 3, a rise more evident in the longer pulse of figure 6. This current increase is accounted for by the temperature rise in the series resistor carbon rods. This same rise is part of the reason for the higher current in figure 4 as opposed to that of figure 3. Variation in the current under supposedly identical conditions is due in part to the presence, for

safety reasons, of 22 contacts in the battery power supply. At the high currents in the circuit, a small resistance change can mean a large current change. In addition, the batteries in the power supply have the characteristic that voltage decreases as current drain increases.

Figure 7 shows a current record for the very beginning of the starting transient. The current rate of rise in this measurement is several orders of magnitude higher than the rate of current rise limit for the silicon controlled rectifier (SCR) switch. This current may be due to charging of the internal capacitance of the SCR. Note that on this timescale, the gate trigger pulse (not shown) is still on its risetime slope and may not have completely turned on the switch. The instrumentation unfortunately prevents a look at the voltage behavior on this time scale.

The actual turn-on pulse of the SCR switch is displayed in figure 8. The rate of rise here is about 1.4 a/μs, well within the design specification of the switch. This slow rise is due to the inductance of the leads from the battery power supply to the experimental apparatus. The duration of the current rise, on the order of tens of milliseconds, is consonant with the design specifications of the SCR. The turn-on pulse holds no surprises.

Turn-off of the arc supply voltage (fig. 9) is accomplished by a process called decommutation, that is, a current pulse from a capacitor counters the current in the SCR switch and, in the absence of a trigger voltage on the switch gate, stops conduction. There is again an extremely rapid high current pulse and a momentary increase in the current flow as the supply tries to discharge the decommutating capacitor. Note that in figures 3 and 6, only one of the high-current, very short pulses has been captured—the stopping transient in figure 3. This is due to the sampling interval in the recording oscilloscope.

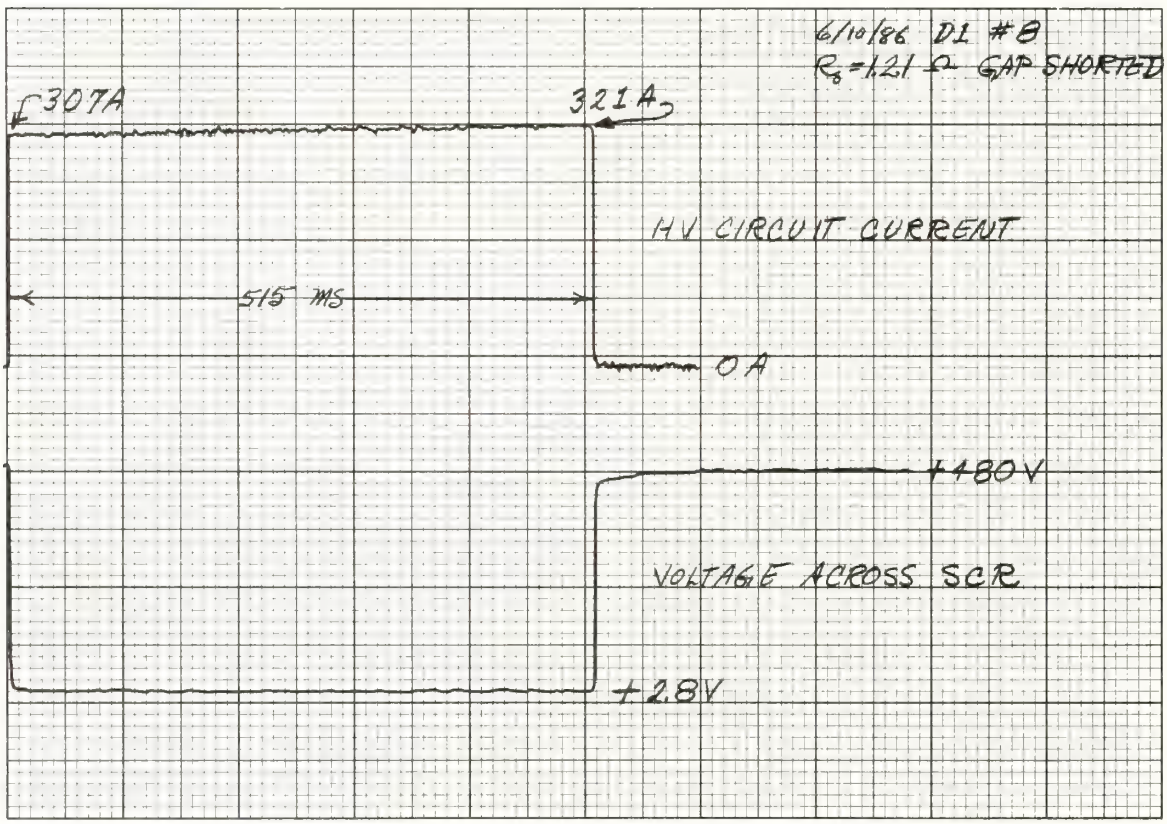


Figure 6—Measurements of the time behavior of circuit current and the voltage across the SCR switch. The effect of heating of the series resistor is apparent.

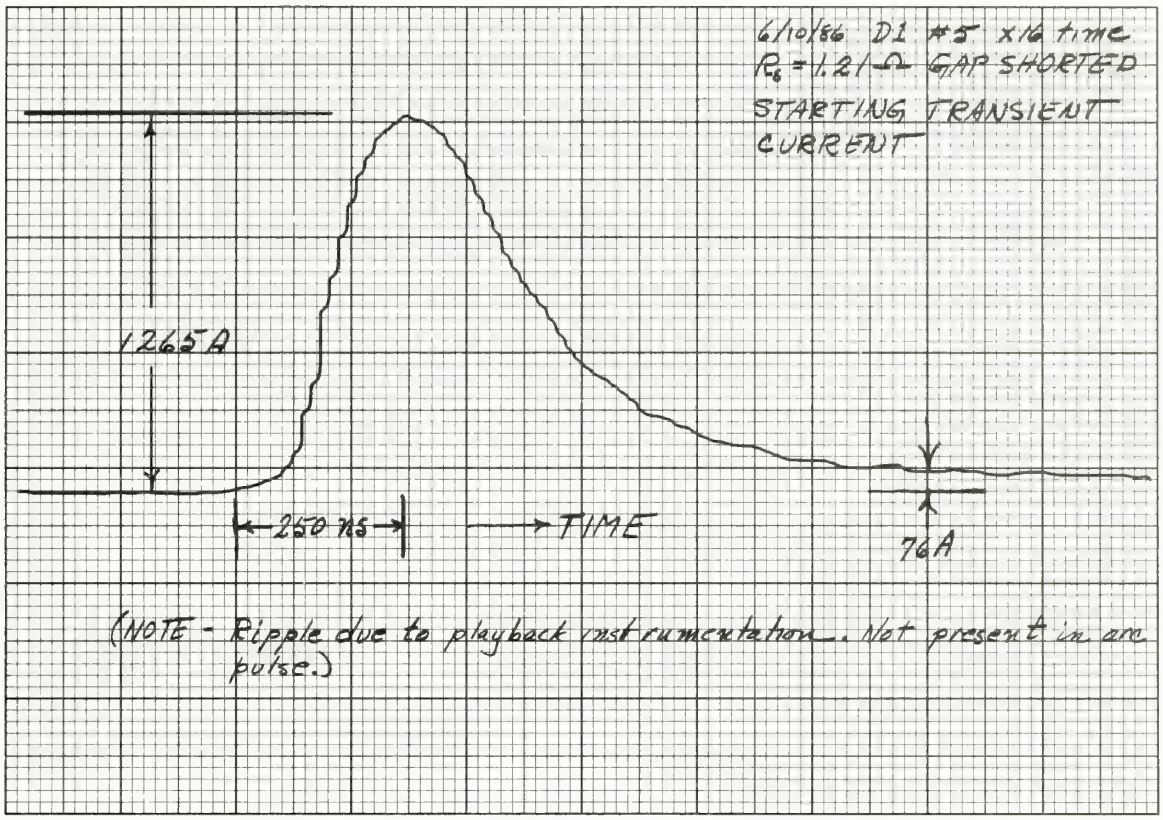


Figure 7—Circuit current behavior with time for the turn-on pulse. Note the large peak current.

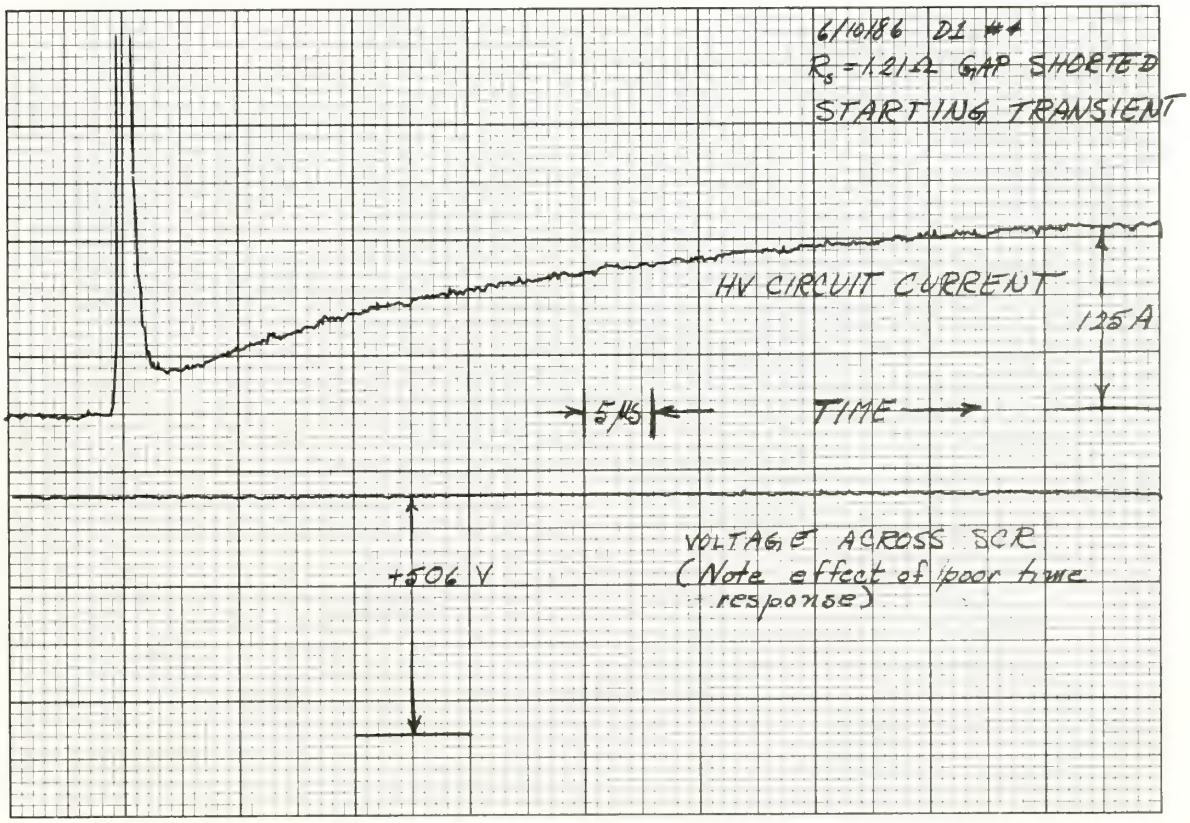


Figure 8—Circuit current behavior with time for the initial 50 microseconds of the turn-on.

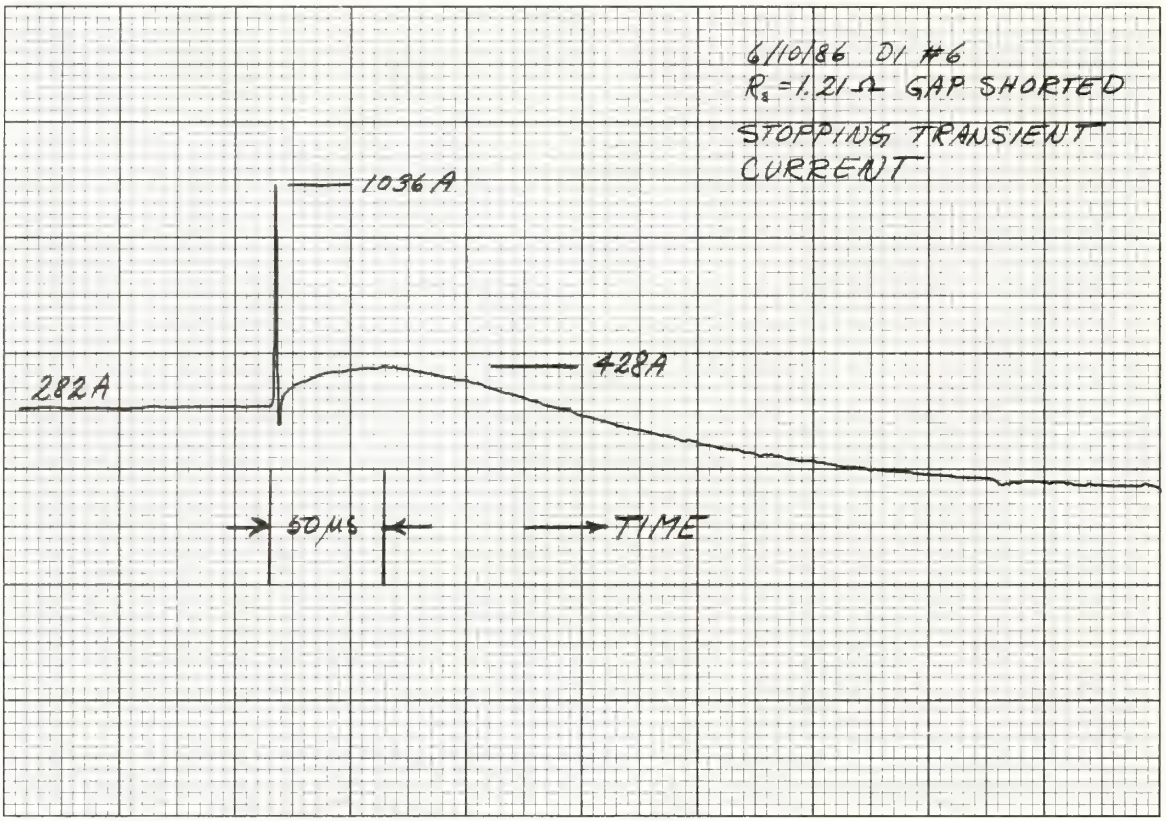


Figure 9—Circuit current behavior for the stopping transient.

GROSS ARC CHARACTERISTICS

Arc behavior is reported in two parts: (1) the current and voltage drop as dependent variables taken as averages over a portion of the arc duration, and (2) the short-term details of current, voltage, and arc structure, the latter as recorded by high-speed video. Current and voltage are read directly from the storage oscilloscope. The period during the arc when the current and voltage are taken is somewhat subjective. The arc must be stable, and sufficient time elapsed from arc initiation for the voltage amplifier to have settled to a steady value. In the traces of figure 2, for example, the current and voltage values would be taken over the last 30 ms of the arc duration.

The data shown in the remainder of the paper were taken using three different geometrical arrangements for the exploding wire ignition system. The first, used until the high-speed video data were obtained, is schematically presented in figure 10. The wire was drawn taut across the edges of the cylindrical electrodes. The belief that the arc would form vertically between the electrodes proved to be incorrect. The slow-motion visual data led to the more concentric ignition arrangement of figure 11. This coaxial structure seems to provide a more stable arc than the simple one of figure 10, although we do not have visual proof. These two methods will be referred to hereafter as "side strike" and "center strike," respectively.

A third striking method (fig. 12) was added to the system to ease ignition studies in peat, punky wood, and short-needled tree duff. The arc apparatus was modified so that an 8-mm-diameter rod could be placed in contact with the anode, the current switched on, and the cathode rod drawn down through the fuel bed. Measurements indicated no significant difference in gross arc behavior. There is, of course, a significant difference in the short-term arc behavior.

The independent electrical variables for the arc experiment are those that are controlled or are controllable. For the arc experiment, these were the gap length (that is, the length between anode and cathode electrodes), the series resistance in the circuit, and the arc duration. We could have controlled the source voltage as well, but would have needed more batteries for this control to be meaningful. The length of the arc is not, as we will show, the same as the gap distance. The dependent electrical variables in our experiment are defined as the current in the arc circuit and the total voltage drop across the circuit.

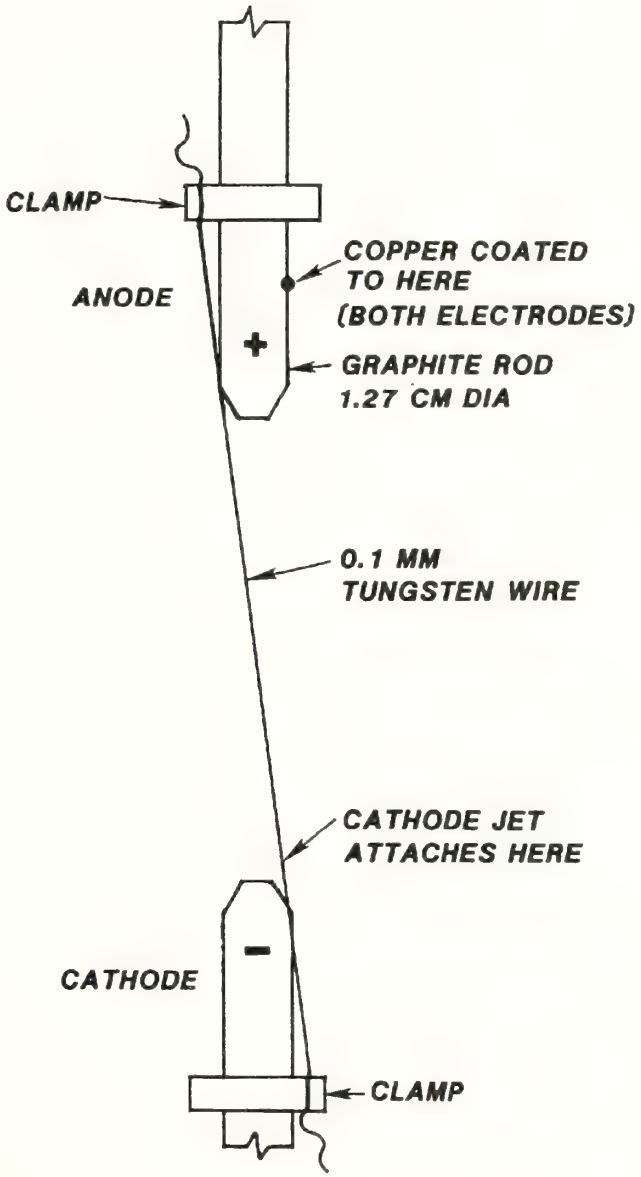


Figure 10—Exploding wire arrangement for the side strike method.

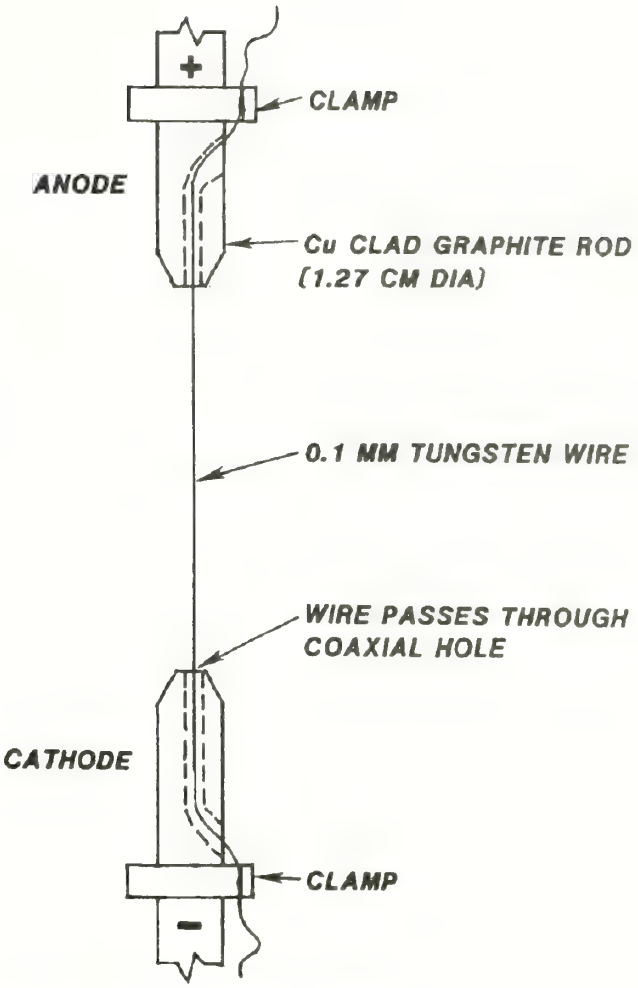


Figure 11—Exploding wire arrangement for the center strike method.

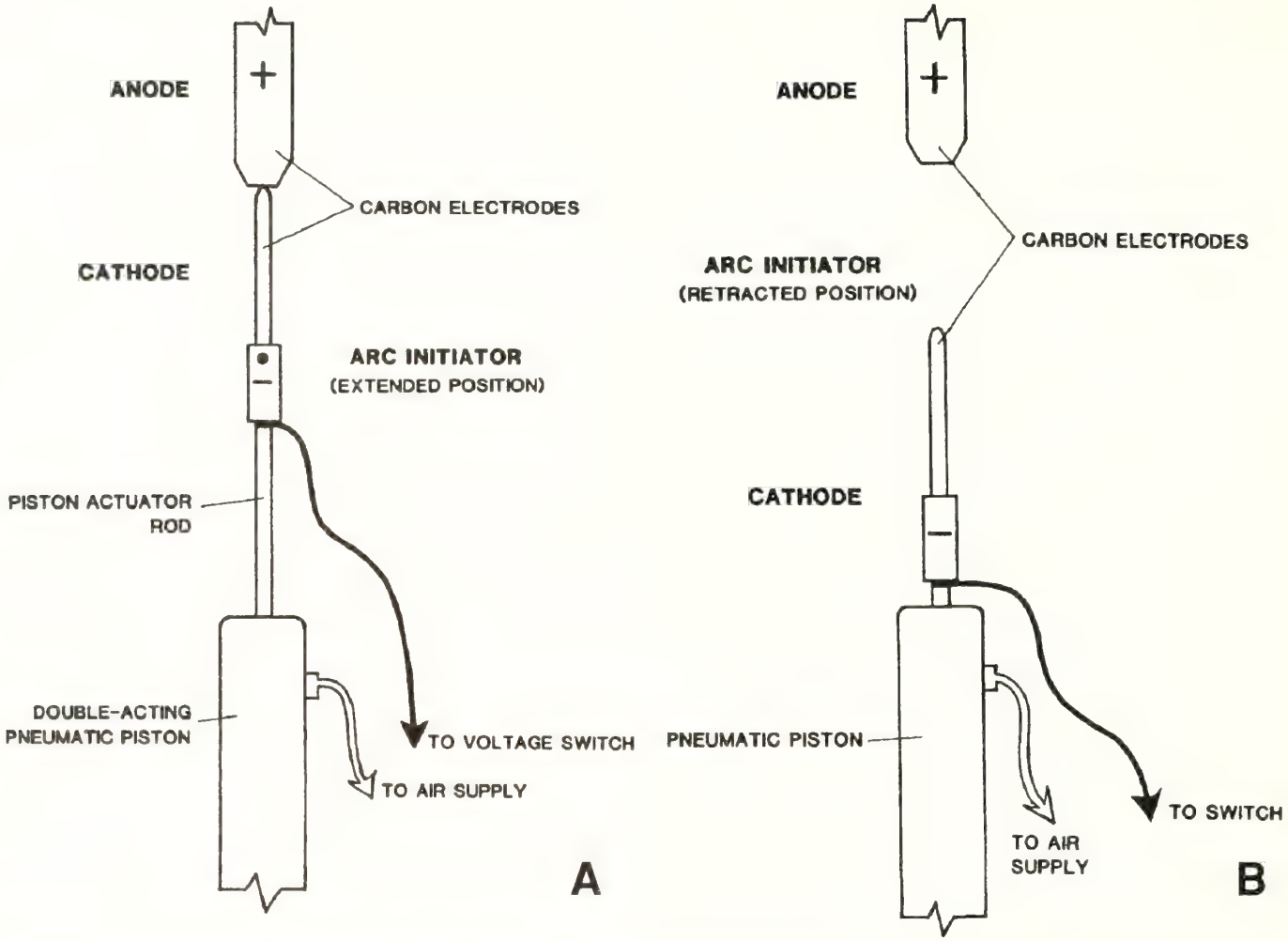


Figure 12—(a) Pneumatic arc initiator in the extended position; (b) the same in the retracted position.

The usual way of reporting arc behavior (see, for example, Von Engel 1965) is by a plot of the arc characteristic. This is a plot of the current in the arc circuit vs. the voltage drop across the arc. Some results from our observations are plotted in this way in figure 13. This figure demonstrates that the voltage drop across the gap is independent, or nearly so, of the current. This was pointed out in Latham (1986) to be a consequence of the free boundary of the arc column, and is not the case for arcs constrained by boundaries or flow control. The scatter in the data points will be explained in the more detailed analysis presented later. The independence of voltage and current was also found, but not explained, by King (1961) for free vertical arcs with about the same gap distances. King also noted a large scatter in his arc data, which he reports as nearly a factor of 2, as did Strom (1946) for very long arcs driven by a 60-Hz source. Strachan and Barrault (1975) report independence of axial electric field from peak current.

Dependence of arc voltage and current for side and center strike as functions of arc gap (GAP) and source conductance (COND) is given in tables 1 through 4 and figures 14 and 15. The figures are based on the analyses in the tables. Data points are not shown on the figures for clarity. As suggested by figure 13, the voltage is very nearly independent of the conductivity, and the current is very nearly independent of the arc gap. Admittedly, we have forced a linear dependence through analysis. The fit of the data, however, is good in case of the voltage (tables 1 and 3), which should be gap-dependent (Latham 1986), and excellent in the case of current (tables 2 and 4), as expressed by the appropriate r^2 values.

Figure 14, voltage across arc vs. the arc gap with conductance as a parameter, graphically demonstrates the near independence of the voltage from conductance. The figure is generated from tables 1 and 2, and gives the results of a linear regression. Linearity is a good assumption for this combination of variables, except for gaps less than 1 cm or so, where cathode and anode flows merge and completely dominate the behavior (see, for example, von Engel [1965], fig. 132, and Sommerville [1959], fig. 6).

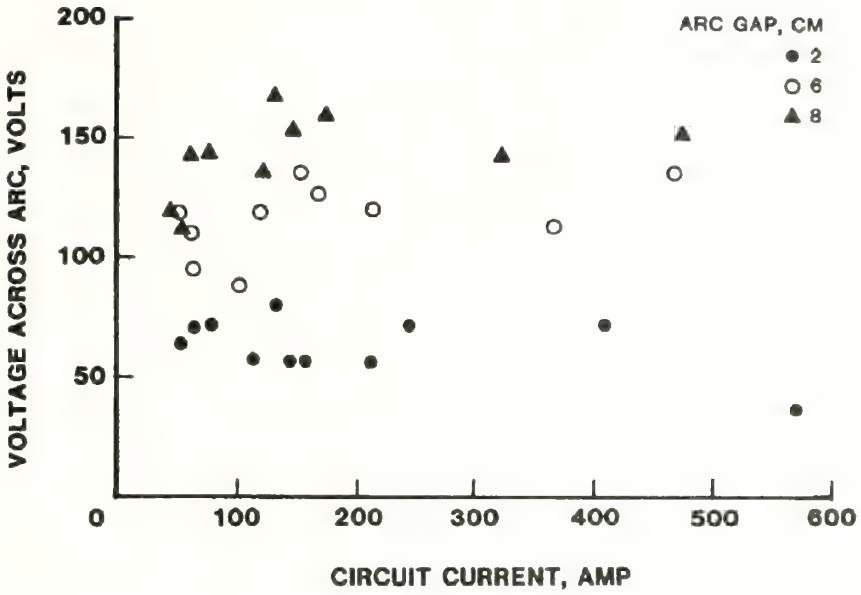


Figure 13—Voltage across the arc as a function of circuit current for three arc gap values.

Table 1—Linear regression for voltage as a function of gap (cm) and source conductance (s) for the side-strike method

	Unweighted least squares linear regression of voltage			
Predictor variables	**Coefficient**	**Std error**	**Student's T**	**P**
Constant	47.881	4.2469	11.27	0.0000
Gap	8.5905	6.7963E–01	12.64	.0000
CS	–3.7067	5.1161	–0.72	.4740

Cases included	35	Missing cases	0
Degrees of freedom	32		
Overall F	95.06	P value	0.0000
Adjusted R^2	.8469		
R^2	.8559		
Resid. mean square	94.30		

	Stepwise analysis of variance of voltage					
Source	**Individual SS**	**Cum. DF**	**Cumulative SS**	**Cumulative MS**	**Adjusted R^2**	**Mallow's CP**
Constant	3.5829E+05					
Gap	1.7878E+04	1	1.7878E+04	1.7878E+04	0.8491	1.5
CS	49.500	2	1.7928E+04	8963.9	.8469	3.0
Residual	3017.4	34	2.0945E+04	616.04		

Cases included	35	Missing cases	0
Degrees of freedom	32		
Overall F	95.06	P value	0.0000
Adjusted R^2	.8469		
R^2	.8559		
Resid. mean square	94.30		

Table 2—Linear regression for voltage as a function of gap (cm) and source conductance (s) for the center-strike method

	Unweighted least squares linear regression of voltage			
Predictor variables	**Coefficient**	**Std error**	**Student's T**	**P**
Constant	45.340	4.5524	9.96	0.0000
Gap	10.985	5.8708E–01	18.71	.0000
CS	9.9032	3.8173	2.59	.0106

Cases included	101	Missing cases	0
Degrees of freedom	98		
Overall F	179.2	P value	0.0000
Adjusted R^2	.7809		
R^2	.7853		
Resid. mean square	294.6		

	Stepwise analysis of variance of voltage					
Source	**Individual SS**	**Cum. DF**	**Cumulative SS**	**Cumulative MS**	**Adjusted R^2**	**Mallow's CP**
Constant	1.4824E+06					
Gap	1.0362E+05	1	1.0362E+05	1.0362E+05	0.7683	7.7
CS	1982.7	2	1.0560E+05	5.2802E+04	.7809	3.0
Residual	2.8870E+04	100	1.3447E+05	1344.7		

Cases included	101	Missing cases	0
Degrees of freedom	98		
Overall F	179.2	P value	0.0000
Adjusted R^2	.7809		
R^2	.7853		
Resid. mean square	294.6		

Table 3—Linear regression for current as a function of gap (cm) and source conductance (s) for the side-strike method

	Unweighted least squares linear regression of current			
Predictor variables	**Coefficient**	**Std error**	**Student's T**	**P**
Constant	33.621	3.3675	9.98	0.0000
Gap	–4.0993	5.3890E–01	–7.61	.0000
CS	320.23	4.0567	78.94	.0000

Cases included	35	Missing cases	0
Degrees of freedom	32		
Overall F	3.595E+03	P value	0.0000
Adjusted R^2	.9953		
R^2	.9956		
Resid. mean square	59.29		

	Stepwise analysis of variance of current					
Source	**Individual SS**	**Cum. DF**	**Cumulative SS**	**Cumulative MS**	**Adjusted R^2**	**Mallow's CP**
Constant	8.5301E+05					
Gap	5.6845E+04	1	5.6845E+04	5.6845E+04	0.1065	6232.3
CS	3.6943E+05	2	4.2628E+05	2.1314E+05	.9953	3.0
Residual	1897.2	34	4.2818E+05	1.2593E+04		

Cases included	35	Missing cases	0
Degrees of freedom	32		
Overall F	3.595E+03	P value	0.0000
Adjusted R^2	.9953		
R^2	.9956		
Resid. mean square	59.29		

Table 4—Linear regression for current as a function of gap (cm) and source conductance (s) for the center-strike method

Predictor variables	Unweighted least squares linear regression of current			
	Coefficient	Std error	Student's T	P
Constant	53.155	4.2888	12.39	0.0000
Gap	−5.4099	5.5308E−01	−9.78	.0000
CS	300.04	3.5962	83.43	.0000

Cases included	101	Missing cases	0
Degrees of freedom	98		
Overall F	3.516E+03	P value	0.0000
Adjusted R^2	.9860		
R^2	.9863		
Resid. mean square	261.5		

Stepwise analysis of variance of current

Source	Individual SS	Cum. DF	Cumulative SS	Cumulative MS	Adjusted R^2	Mallow's CP
Constant	2.9168E+06					
Gap	1.8643E+04	1	1.8643E+04	1.8643E+04	0.0000	6961.9
CS	1.8200E+06	2	1.8387E+06	9.1933E+05	.9860	3.0
Residual	2.5623E+04	100	1.8643E+06	1.8643E+04		

Cases included	101	Missing cases	0
Degrees of freedom	98		
Overall F	3.516E+03	P value	0.0000
Adjusted R^2	.9860		
R^2	.9863		
Resid. mean square	261.5		

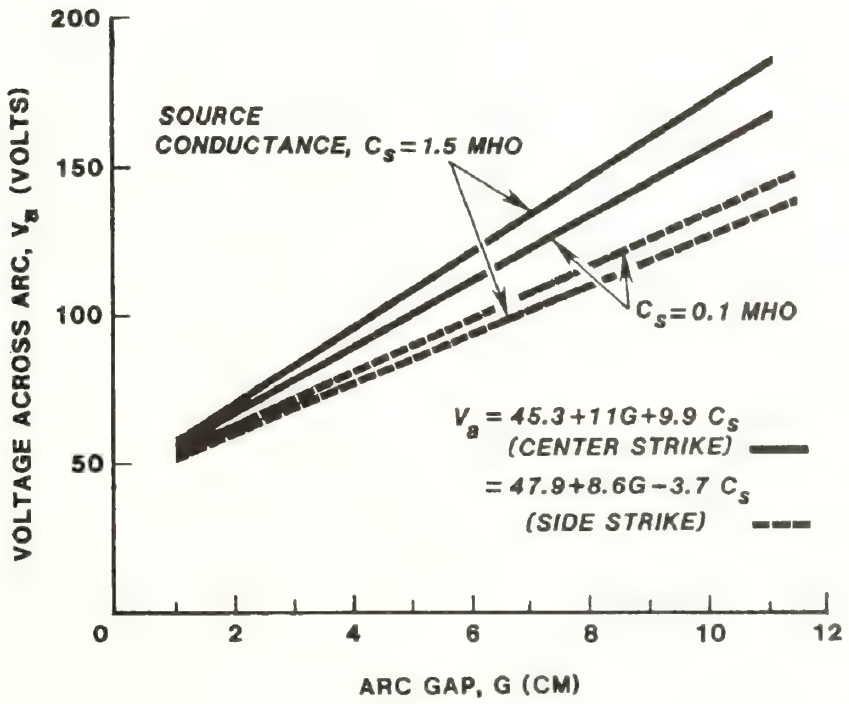


Figure 14—The voltage drop across the arc as a function of arc gap for two values of series conductance. Results of analysis of side-strike and center-strike methods are shown.

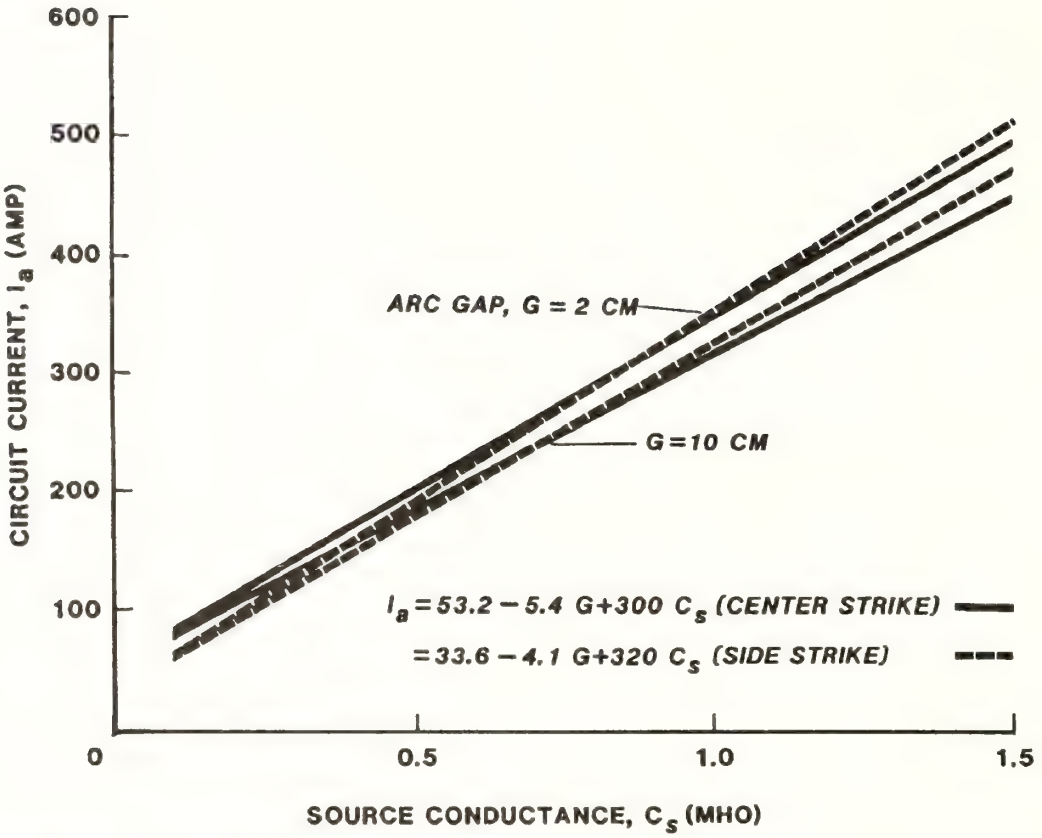


Figure 15—Circuit current presented as a function of source conductance for two arc gaps. Results of analysis of side-strike and center-strike methods are shown.

The slope of the voltage curves gives the mean electric field for arcs longer than 1 cm. If flow structure is not important, there should be little difference between side strike and center strike results. There is some difference in these figures; 11 V/cm in the center strike case and 8.6 V/cm in the side strike. This indicates that the side strike arcs may be in some way shorter than the center strike arcs, or that the structure of the anode and/or cathode columns are different. We have no way of determining the difference at present. Strom's (1946) arcs were 25-50 cm long, and had electric fields which, although showing large scatter, averaged 13 V/cm, close to our values of 8 and 11 V/cm.

The dependence of the voltage across the arc on source conductance is very small, and changes sign according to the striking method (tables 1, 2), being negative for side strike and positive for center strike (fig. 14). The statistics in the tables also show that if the arc voltage drop is related to conductance, the relationship is very weak indeed. Figure 13 demonstrates also that the current and voltage are independent from each other. The noise in the measurements on figure 13, together with the sign change in dependence, means that there is no apparent systematic relationship between voltage and current and, for our circuit, its surrogate, conductance.

The anode and cathode each has an associated voltage drop. The sum of these is the intercept of the voltage vs. gap curves in figure 14 (from tables 1 and 2). These values, 45.3 V for the center strike arcs and 47.9 V for the side strike arcs, are reasonable according to von Engel (1965) (see the figure cited above). The actual "electrode drop" is somewhat less than the intercepts given above, and is highly dependent on the electrode structure, material, and the "working gas." We did not investigate this phenomenon in this study.

Figure 15 and tables 3 and 4 summarize the relationship between current and arc gap and circuit conductance. The statistics in the tables demonstrate clearly that the possibility of systematic dependence of current on arc gap is small. The addition of the gap variable to the regression adds essentially no new information. Again, as with voltage, we must be careful to state the limitations of this analysis. Arcs shorter than 1 cm or so will not follow the equations developed here. In addition, there is the possibility that substantially longer arcs, or higher current arcs, may not either. Because there should be no current flow at zero conductance (infinite series resistance), it is certain that the linear analysis will fall apart at conductances less than 0.1 S or so, as is evident from figure 16.

That the current does depend slightly on electrode gap is apparent from figure 16. In general, as the current increases, the dependence becomes stronger. For currents less than 100 a, the dependence is so weak that it seems to vanish. Lengthening the gap seems to cause the current to decrease for a given source conductance. Thus, even though the source conductance is the major factor

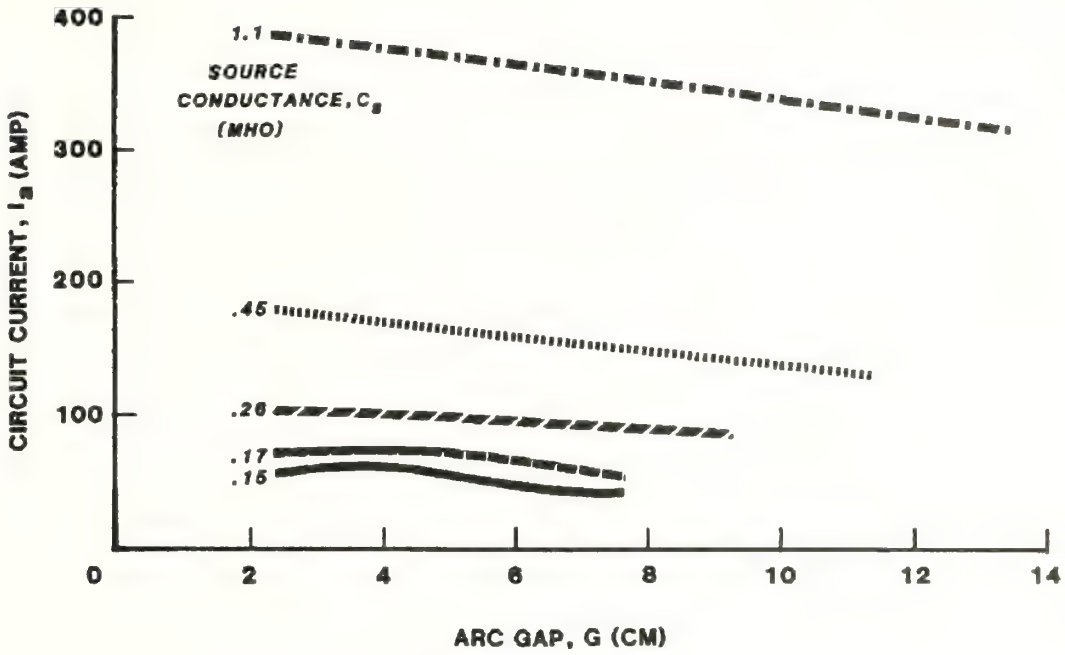


Figure 16—Circuit current as a function of arc gap for four values of source conductance.

determining the current flow, the arc length does have an effect. This still does not mean that the current and the voltage drop are significantly related. Before expanding further on the current and voltage drop of the arc, we need to look at the details of arc behavior with time.

RESULTS OF EXPERIMENTS—DETAILED ARC TIME BEHAVIOR

From consideration of the overall arc parameters, we turn to the details of the time behavior. A typical arc cycle was presented in figure 2. The current trace displays the initial pulse (1), followed by a drop in current for about 200 to 300 μs (2), then a current rise (3), a noisy period followed by a quiet high-current flow (4), and the turn-off pulse (5). We will consider these phases of the total arc duration separately.

Figure 17 is a single frame from a 1,000 frame/s video system. The 0.1-mm-diameter tungsten wire is heated by the circuit current. In the appendix, a simple analysis predicts a duration of about 135 μs. The appendix calculation does not take into account the radiative losses as the wire heats, which would make the time somewhat longer. Figure 18 presents current in the wire and light output as a function of time for the wire heating phase of the arc. The current trace has a high initial peak, as we saw in the shorted case of figure 7. This represents charging of the SCR capacitance. The actual turn-on time of the SCR is reflected in the slow rise, peaking at about 35 μs from initiation. At this point, the wire begins to heat, as can be seen from the light output trace. The heating time can be seen on the trace as somewhat longer than the 135 μs as calculated. The events labeled B and C on figure 18 are present on all the traces we have looked at in this detail, but in the absence of detailed photography, we do not know what phenomenon causes them. Event C may well be the creation of a local hot spot and the beginning of the disintegration of the wire. There is no corresponding variation in the current, but the presence of a local small break would not necessarily cause a noticeable change in current flow. The same events for a different arc are evident in figure 19. Here, event B occurs later than in the example of figure 18. The former figure illustrates the connection of event B to the wire separation or perhaps to the beginnings of the formation of the arc, corresponding to the period calculated in the appendix. The current rise subsequent to event B is from the arc-striking process.

Subsequent to the wire heating and breaking or disintegrating, the arc strikes in the ionized column left behind. A time history of this part of the arc duration is shown by figures 20 and 21. Here, the wire heating phase is short and not well-defined. Voltage instead of light output was recorded for this event (there are only two channels in the recording oscilloscope). In figure 20a, the anode can be seen under the "E" in "Ektapro" and the cathode is just out of the picture between the "A" and "Y" of "PLAY." Refer to figure 10 again for the physical layout. In figure 20a, the wire has disintegrated, leaving behind remnants of burning tungsten, seen as the bright dots in the figure, a-f. The anode and cathode jets have begun to form, can just be seen in figure 20a, and are apparent in figures 20c-20f. The time elapsed between figures 20a and 20f is 13 ms.

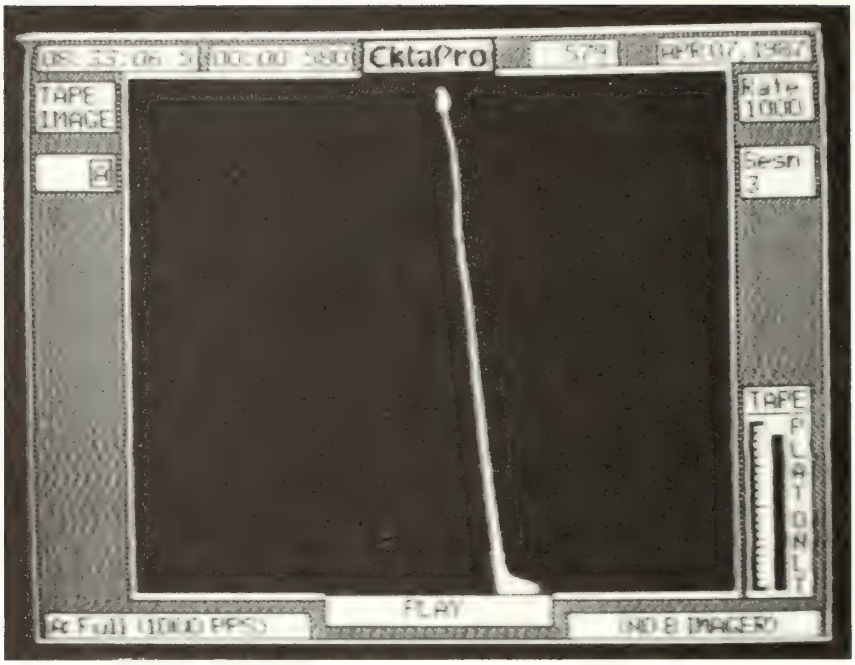


Figure 17—A frame of fast video recording of the wire heating part of arc formation.

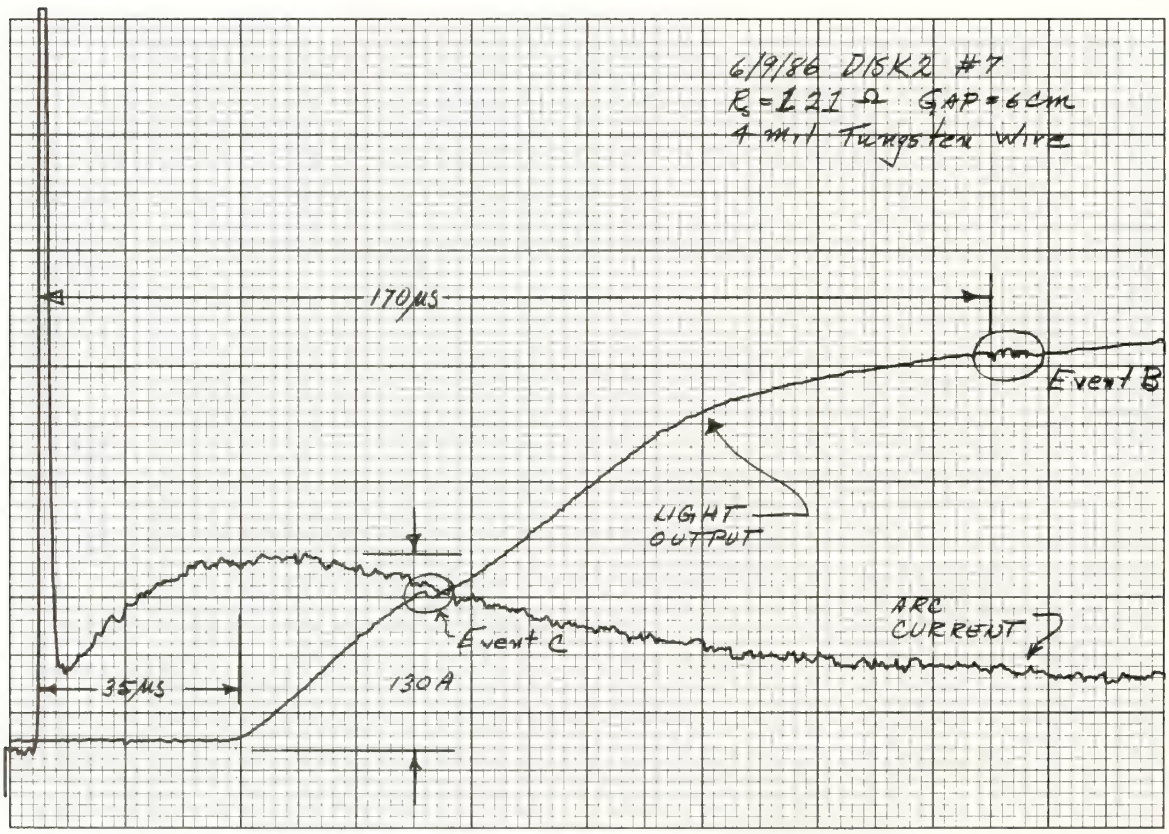


Figure 18—A high time resolution record of circuit current and arc luminosity for the wire heating part of arc formation.

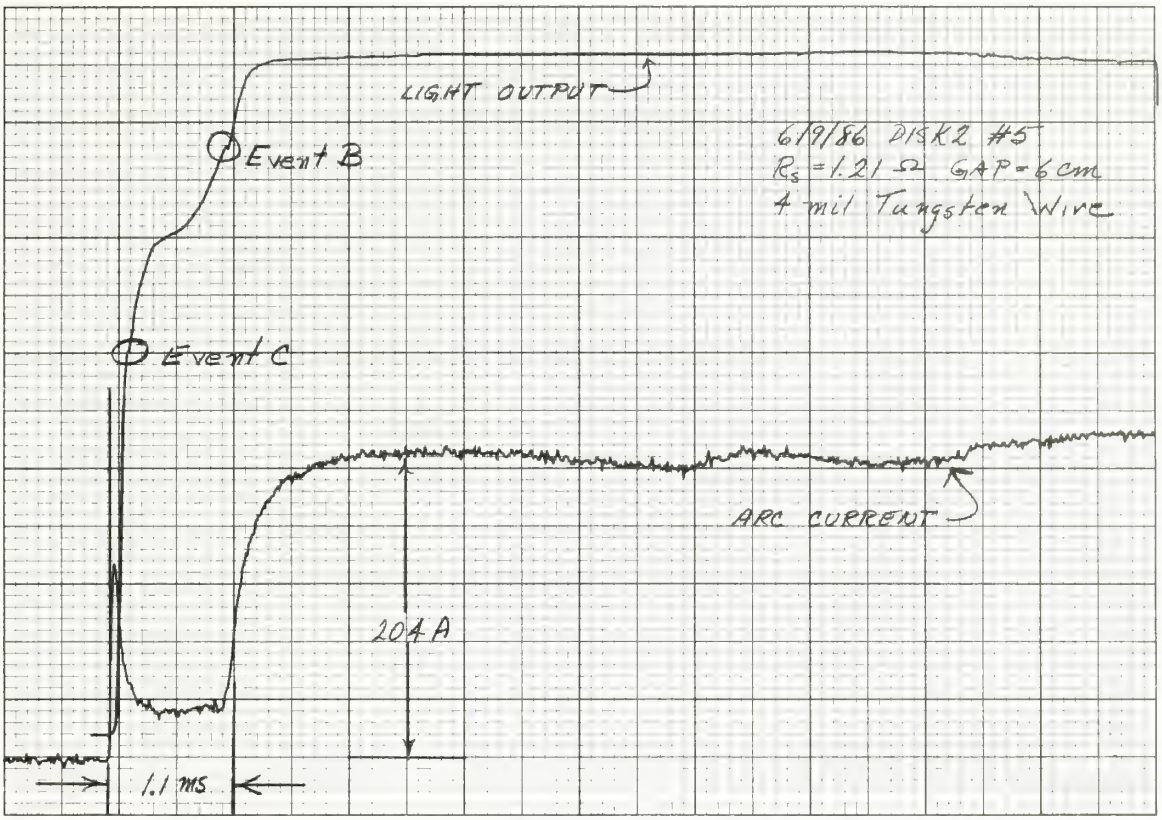


Figure 19—A medium resolution record of wire heating and arc striking parts of arc formation.

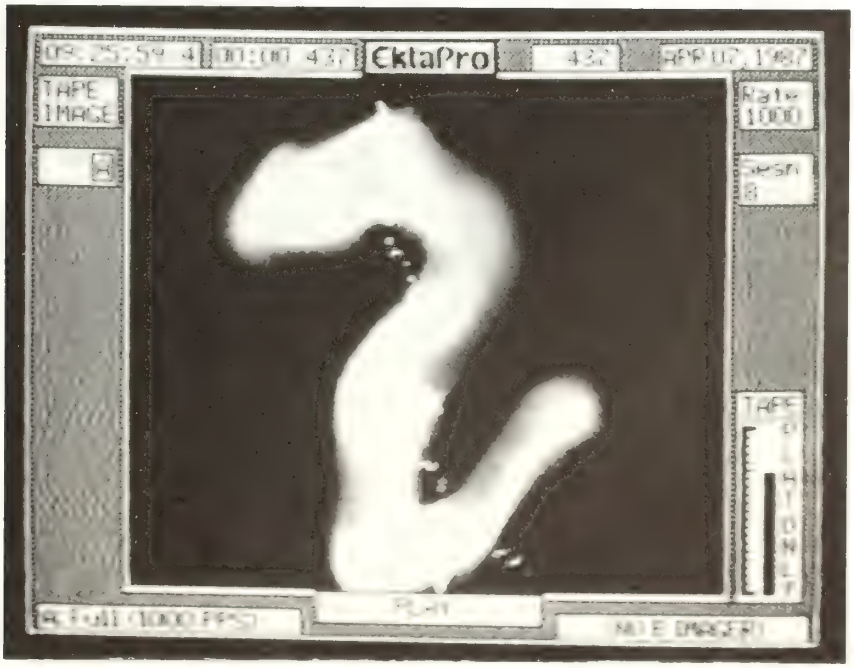
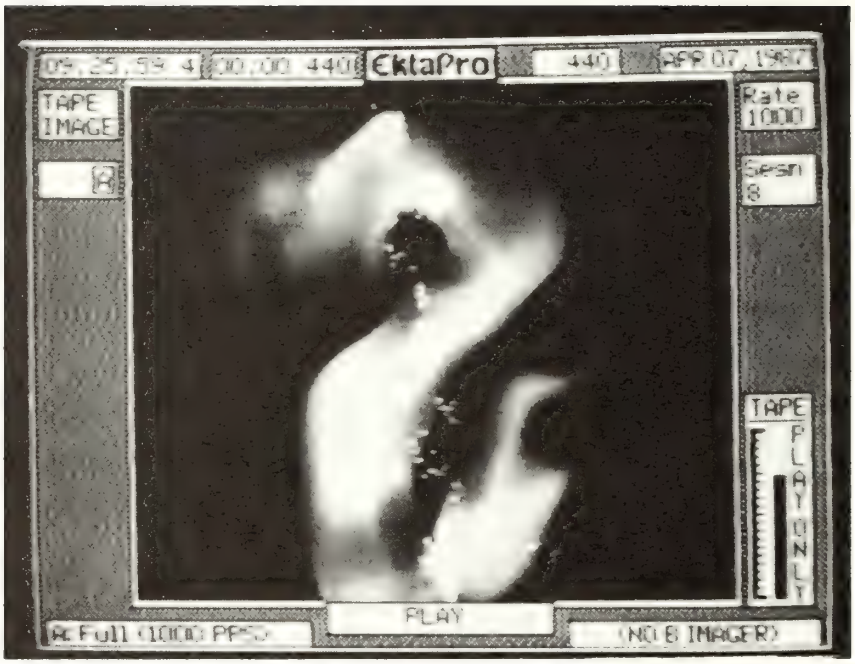
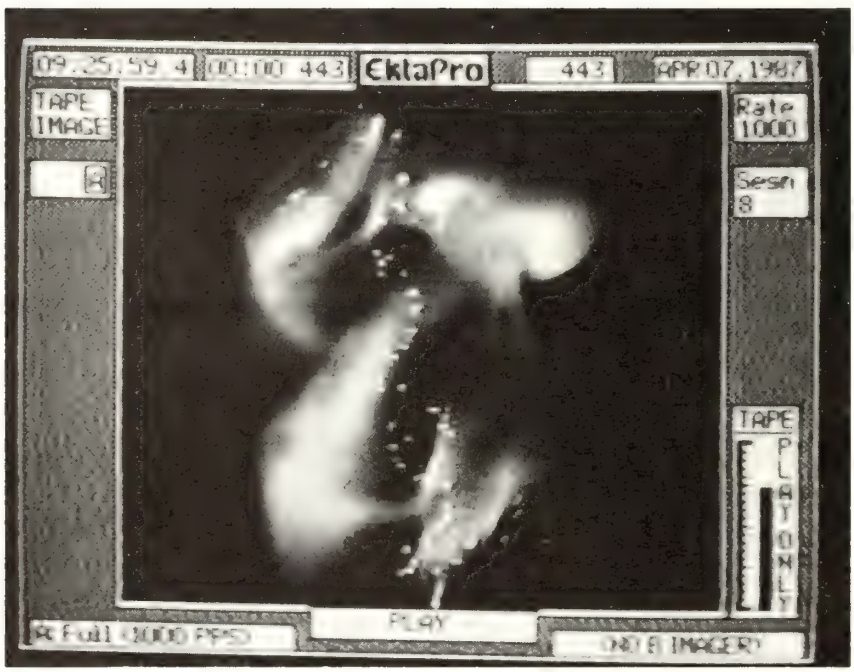


Figure 20—Successive frames (a-f) from a fast video recording of the formation part of an arc discharge.

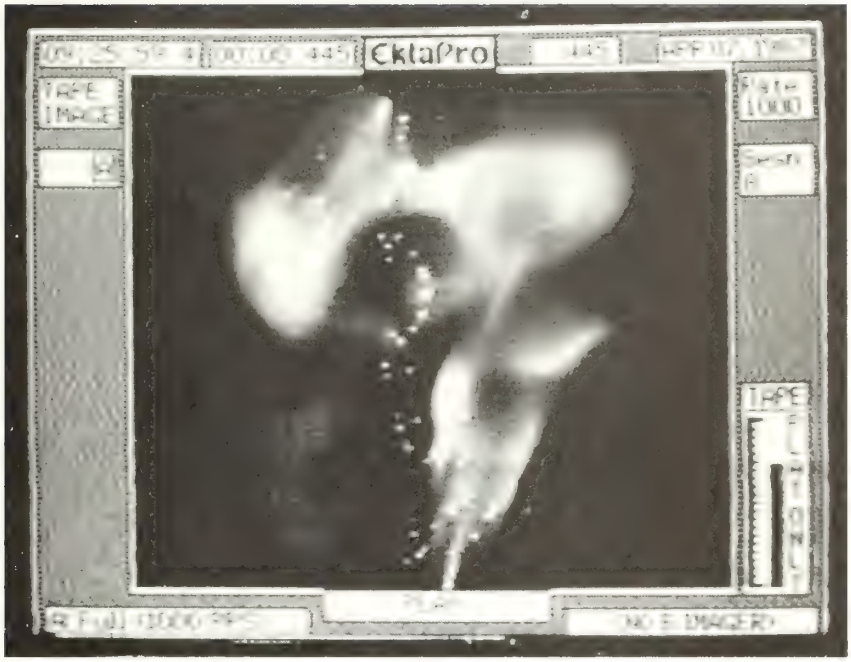


b

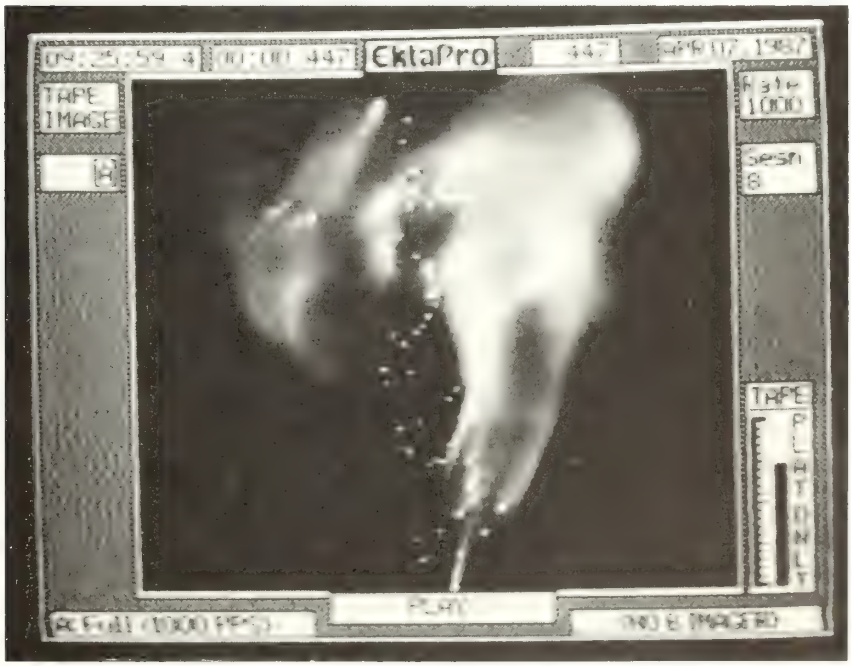


c

Figure 20 (Con.)

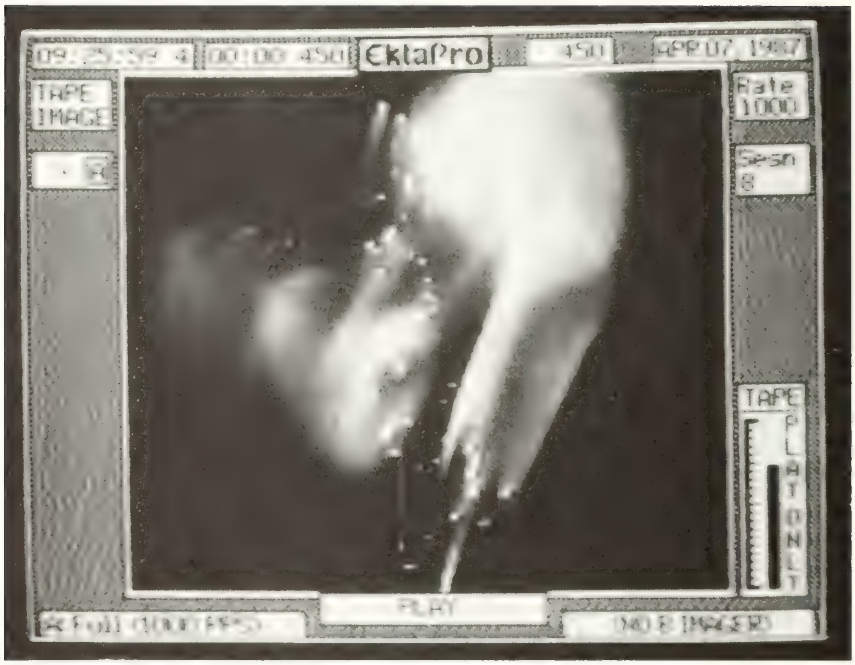


d



e

Figure 20 (Con.)



f

Figure 20 (Con.)

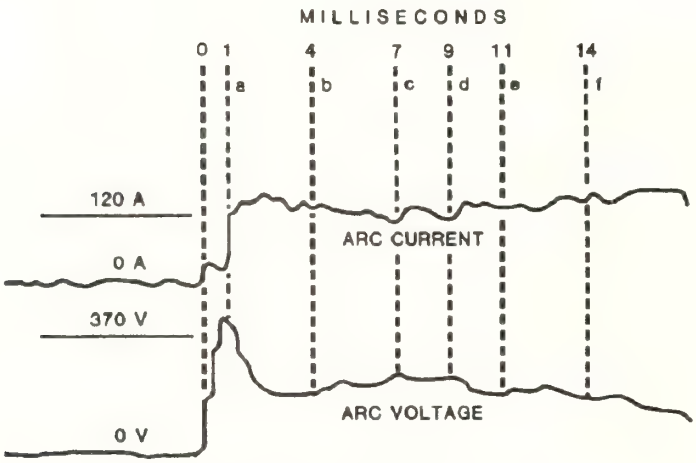


Figure 21—The current and voltage record accompanying figure 20. Note the keys to that figure.

We have correlated the images of figure 20 to the current and voltage traces of figure 21. Initial current and voltage spikes are missing and the voltage trace is ragged at the onset (between 0 and 1 ms) because the time scale was expanded for this measurement; there are five sample values between these points. Despite the violent and transitory nature of the hot gases in the arc, the current and voltage traces seem rather quiet; they do reflect the changes in the arc gas structure, but the variations are about 10 to 15 percent of the peak value. In general, the more tenuous and torturous the path, the lower the current, as for example at c and d of figures 20 and 21. As the path shortens, and the image brightens, the current increases, as at f (figs. 20 and 21). This behavior is consistent with the known characteristics of hot air conductivity as a function of temperature. Between 4,500 K and 10,000 K, the conductivity of air is very nearly constant. This means that even though the brightness of the arc as seen by the video camera might vary significantly, the conductance of the arc will not vary by much. Length changes, on the other hand, will have a direct effect on arc conductance, with the current decreasing as the arc length increases. In this case, the voltage is affected as well.

The voltage at the time the arc strikes (point a, figure 21) was called the striking voltage. Although the voltage displayed is less than the true voltage because of the time lag in the voltmeter, it is nonetheless instructive to consider how striking voltage varies with arc gap and source conductance. This is done in table 5 and figure 22. The analysis presented in the table indicates that the conductance has little to do with the striking voltage. This means that the breakdown of the path depends only on the voltage across the gap in the ionized medium for the conductance values attainable with this apparatus. The electric field at the time of striking the arc is, from figure 22, about 37 V/cm, again probably lower than the true value. Apparently, there is a problem with maintaining the arc for gaps greater than 10 cm. The voltage drop at striking would be on the order of 400 V by measurement.

Table 5—Linear regression analysis for arc striking voltage as a function of gap and source conductance for the side-strike method

	Unweighted least squares linear regression of voltage			
Predictor variables	**Coefficient**	**Std error**	**Student's T**	**P**
Constant	104.71	9.7674	10.72	0.0000
Cond	−21.116	12.493	−1.69	.1021
Gap	34.851	1.6391	21.26	.0000
Cases included	31	Missing cases	4	
Degrees of freedom	28			
Overall F	284.1	P value	0.0000	
Adjusted R^2	.9497			
R^2	.9530			
Resid. mean square	469.5			

	Stepwise analysis of variance of voltage						
Source	**Individual SS**	**Cum. DF**	**Cumulative SS**	**Cumulative MS**	**Adjusted R^2**	**Mallow' CP**	**P**
Constant	3.1215E+06						
Cond	5.4509E+04	1	5.4509E+04	5.4509E+04	0.1670	453.1	2
Gap	2.1224E+05	2	2.6675E+05	1.3337E+05	.9497	3.0	3
Residual	1.3146E+04	30	2.7989E+05	9329.8			
Cases included	31		Missing cases	4			
Degrees of freedom	28						
Overall F	284.1		P value	0.0000			
Adjusted R^2	.9497						
R^2	.9530						
Resid. mean square	469.5						

	Unweighted least squares linear regression of voltage			
Predictor variables	**Coefficient**	**Std error**	**Student's T**	**P**
Constant	104.37	10.073	10.36	0.0000
Gap	33.427	1.4502	23.05	0000
Cases included	31	Missing cases	4	
Degrees of freedom	29			
Overall F	531.3	P value	0.0000	
Adjusted R^2	.9465			
R^2	.9482			
Resid. mean square	499.5			

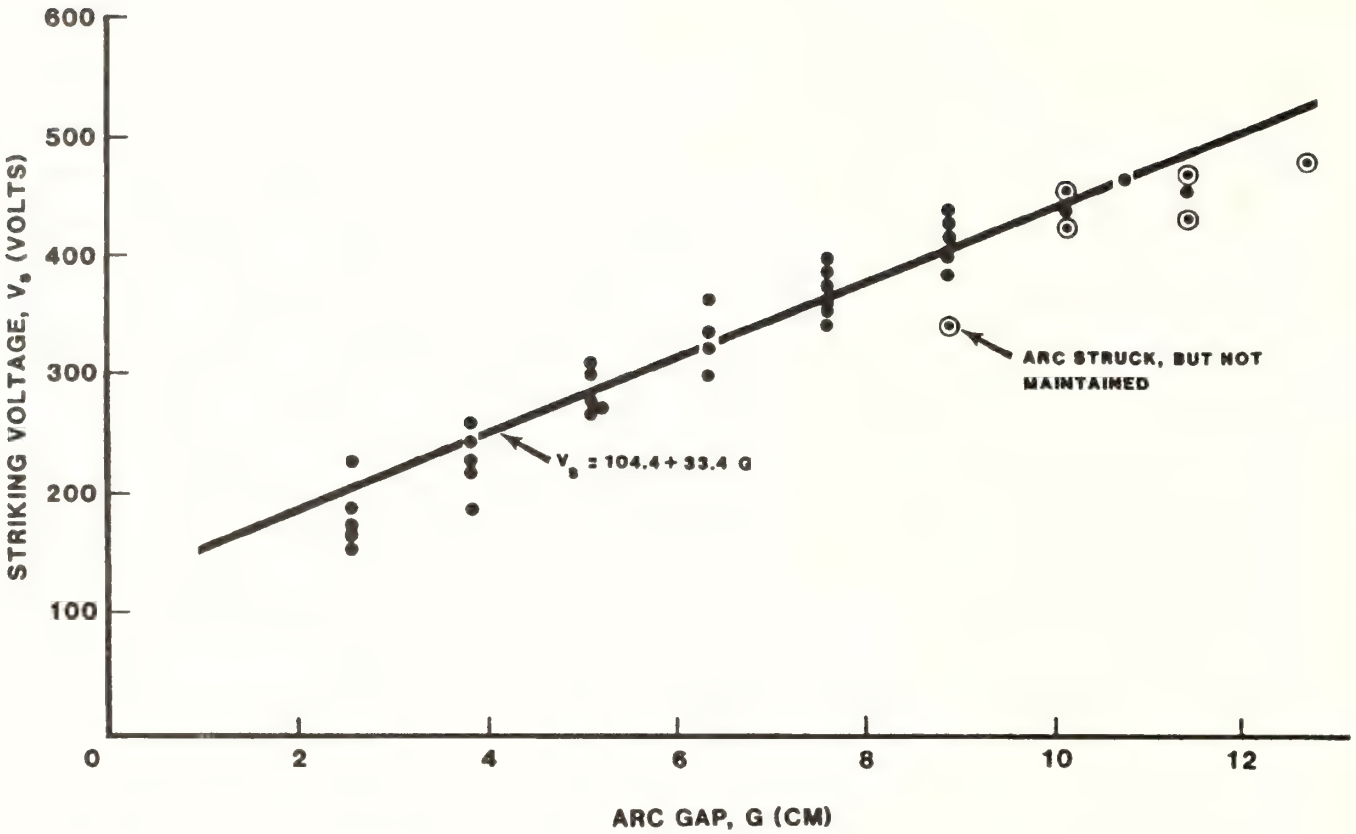


Figure 22—The voltage drop across the arc as it strikes as a function of arc gap.

The current at striking is on the order of 10 A, and the voltage drop in the external circuit is about 100 V. The small effect which might be present due to the source conductance is masked by experimental noise.

The striking mechanism was examined by Vlastos (1973). Although the voltages in his exploding wire experiments were higher than ours by more than a factor of 2, the mechanism he gives for "low" voltage sources is, from the fast video evidence, the one at work in our study. The wire heats slowly, relative to heating rates for 10 kV sources, and no shock wave forms from the rapid heating. Because there is no shock wave, and the wire heats slowly, there is an ion cloud formed around the wire, and it is in this medium that the arc forms. This is clear from figure 20a and b, where the hot gas cloud containing the discharge has moved away from the remains of the wire, seen as hot spots between the cathode and the anode. The column of gas has moved away because of buoyancy and the electromagnetic forces. Note that the separation of the trigger wire may be event c in figure 19. This is suggested by the presence of a "dwell time" in Vlastos' data; a time between wire breaking and arc formation. The dwell time in our data seems to be on the order of 1 ms, 20 times Vlastos' longest dwell time. This is expected from the lower voltage available in our apparatus, as an extrapolation of his data indicates.

Striking of the arc with the "pull-down" pneumatic cylinder apparatus is quite different, as can be seen from figures 23 and 24. Here, the arc forms as the cathode travels away from the anode. The cathode jet is always well formed, but its extension rate may or may not be sufficient to keep up with the withdrawal rate of the cathode. The voltage and current traces show the gradual decrease of current as the arc lengthens and settles into a steady state. There is a 33-ms delay between the current turn-on pulse and the beginning of the cathode motion because of computer timing delay. The actual motion of the cathode starts after this delay, and proceeds for about 60 ms (figs. 23, 24). Note that there seems to be a "second strike" in the case shown in figure 24. Because we do not have high-speed visual data, we cannot yet say what the cause is for this behavior. It may be that the formation of the cathode and anode jets simply cannot proceed as fast as the cathode is withdrawn in some cases.

The arc does not deviate to one side as much as in the wire experiments because we have moved the anode supply wire so that it is on the arc axis rather than perpendicular to it. The trace after the cathode has reached full extension is very well behaved by comparison with the exploding wire experiments. Details of the pulled arc are not yet available.

The effect of hydrodynamic instability and the perpendicular lead is apparent from the behavior of the arc subsequent to striking, as shown in figures 25, 26, and 27. Figure 27 is the fast video, and is about one cycle of the current and angle traces of figure 26. The video data

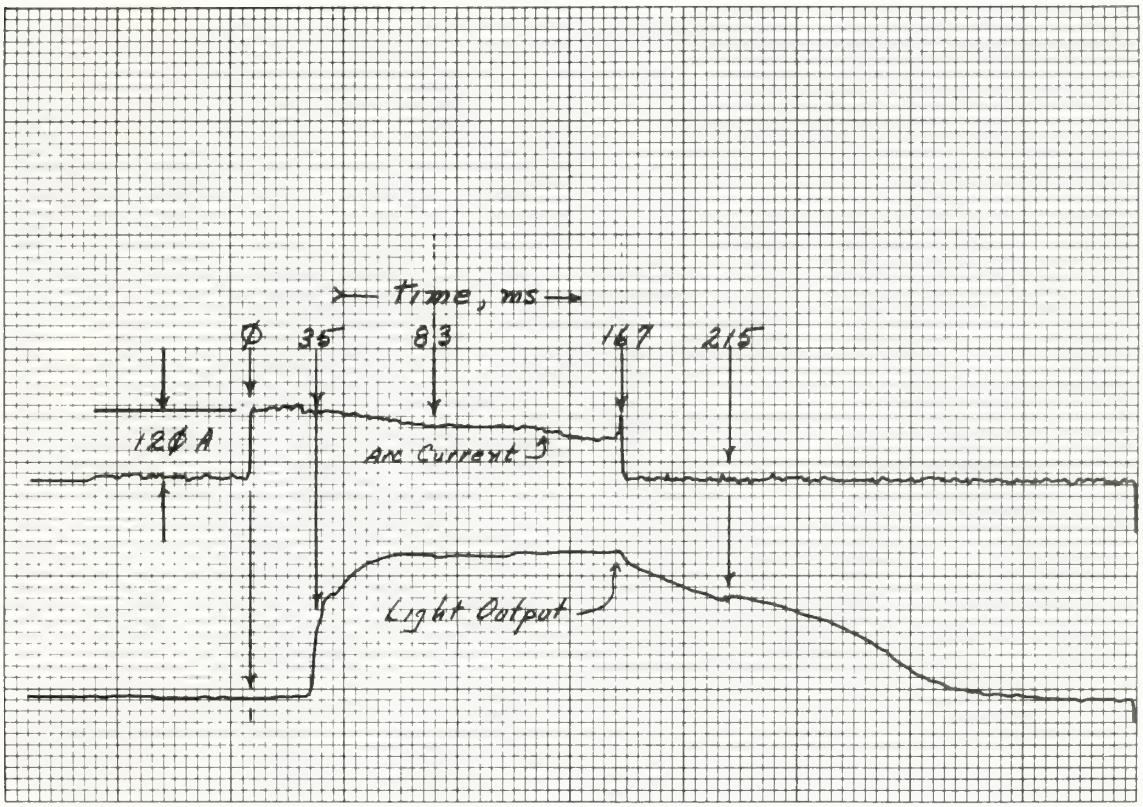


Figure 23—Arc current and luminosity records for "pull-down" ignition.

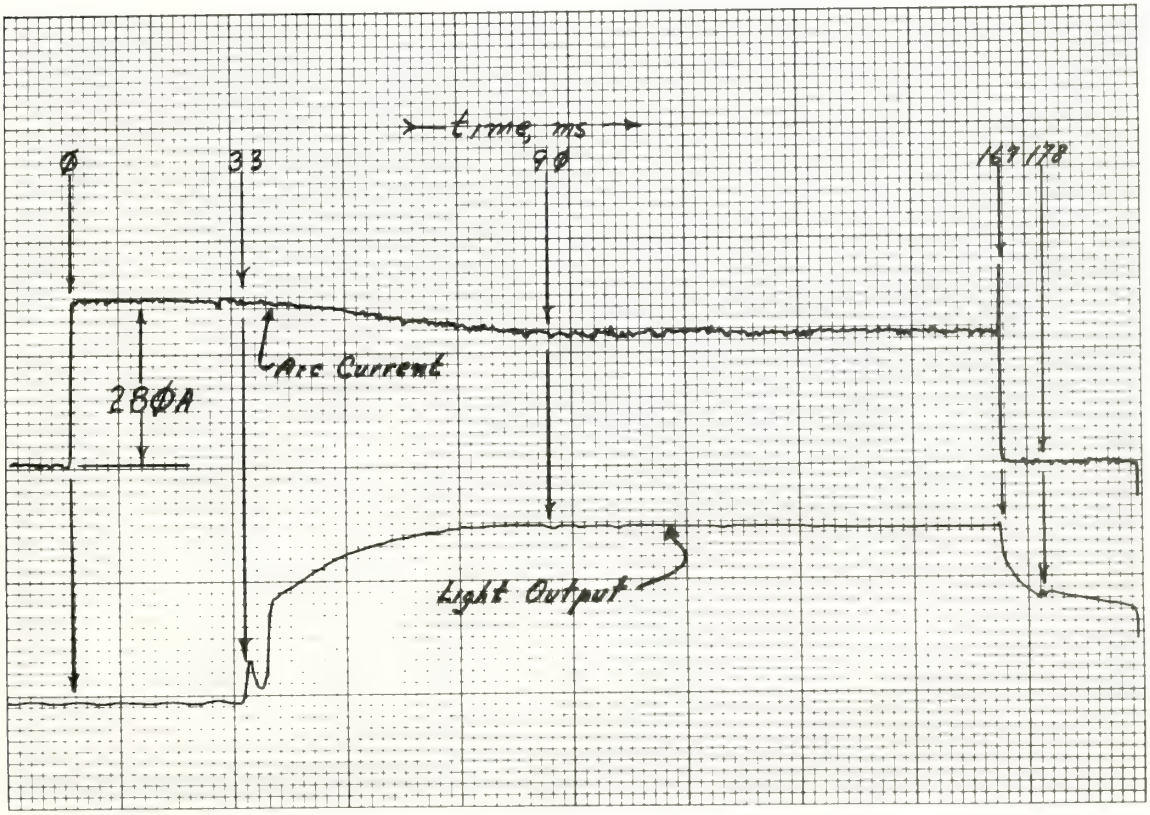


Figure 24—As figure 23, showing a second strike.

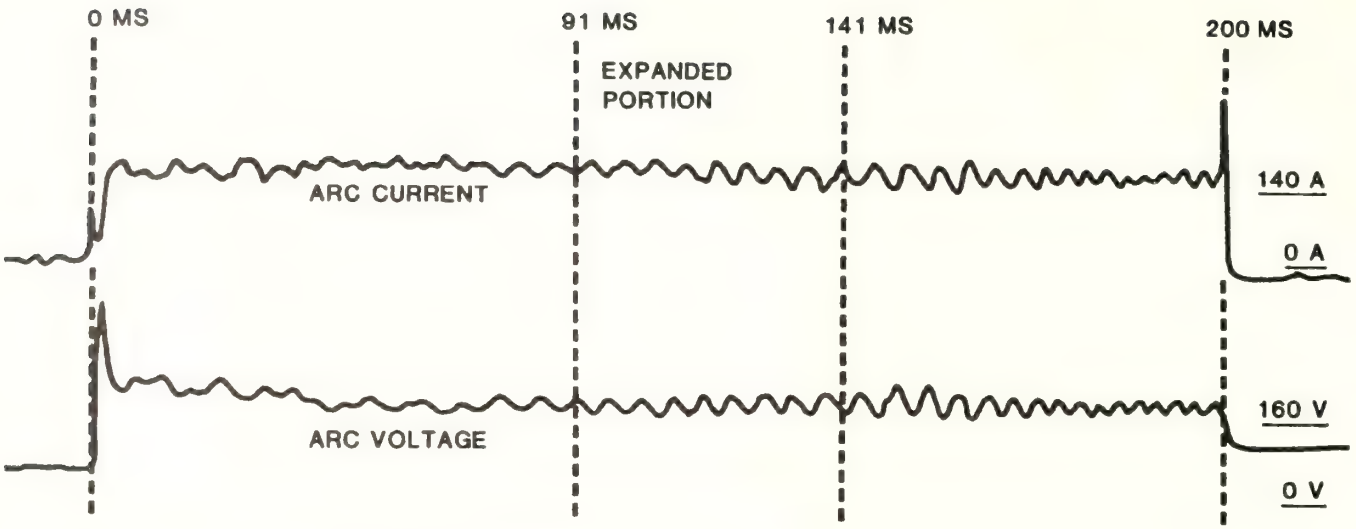


Figure 25—Current and voltage records for an oscillating arc.

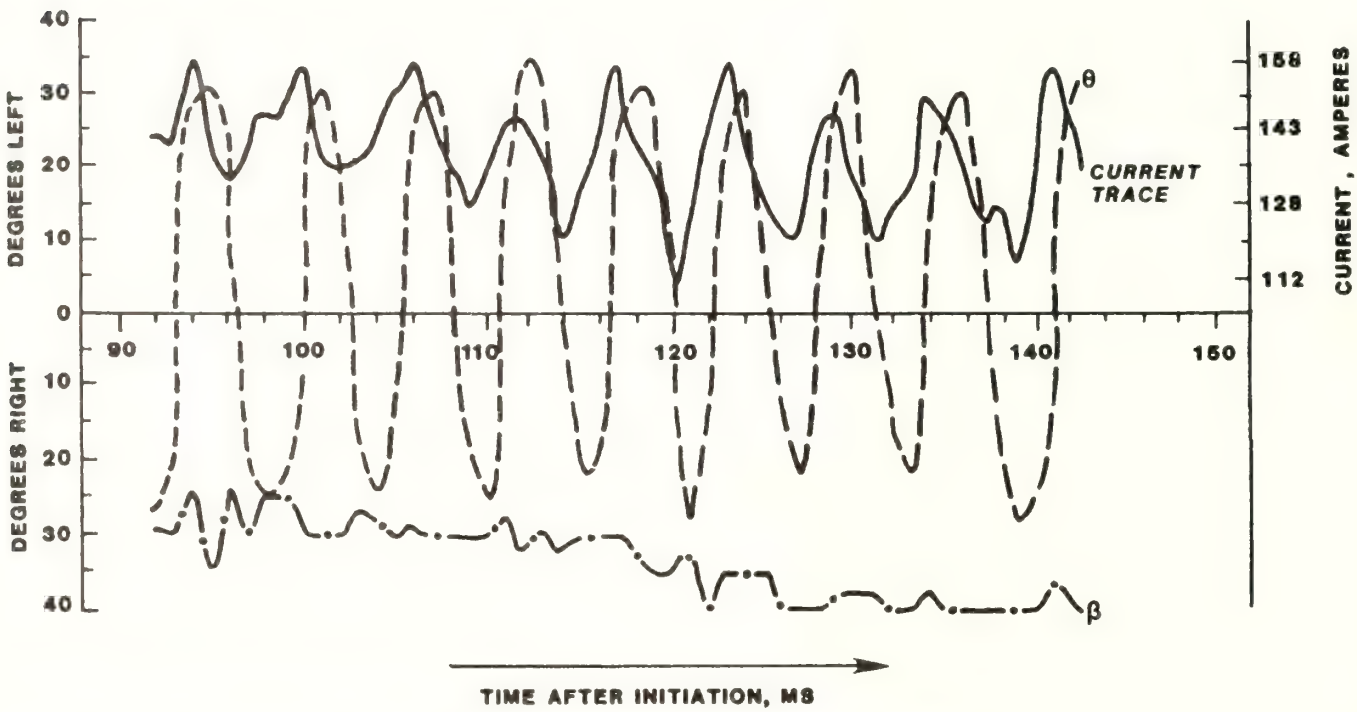
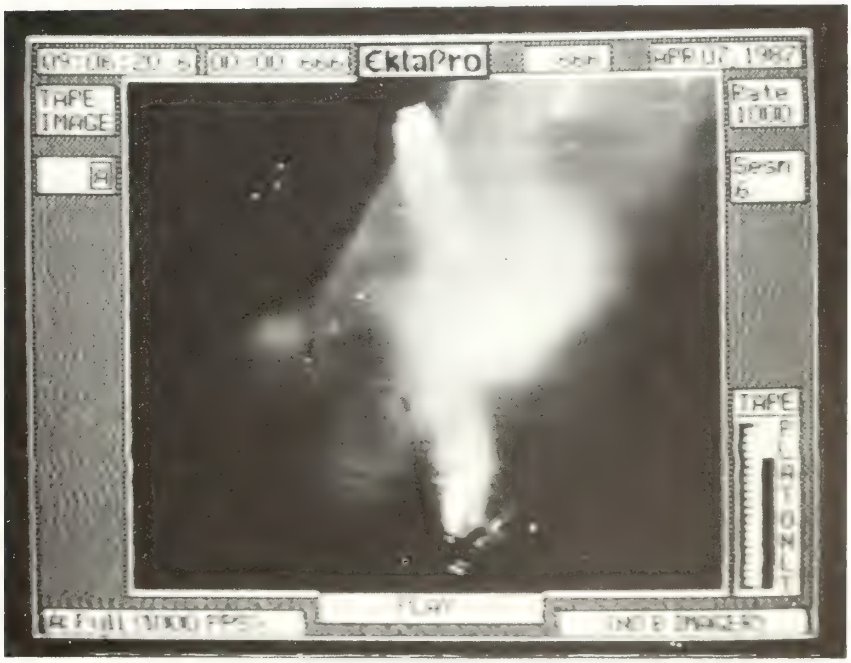


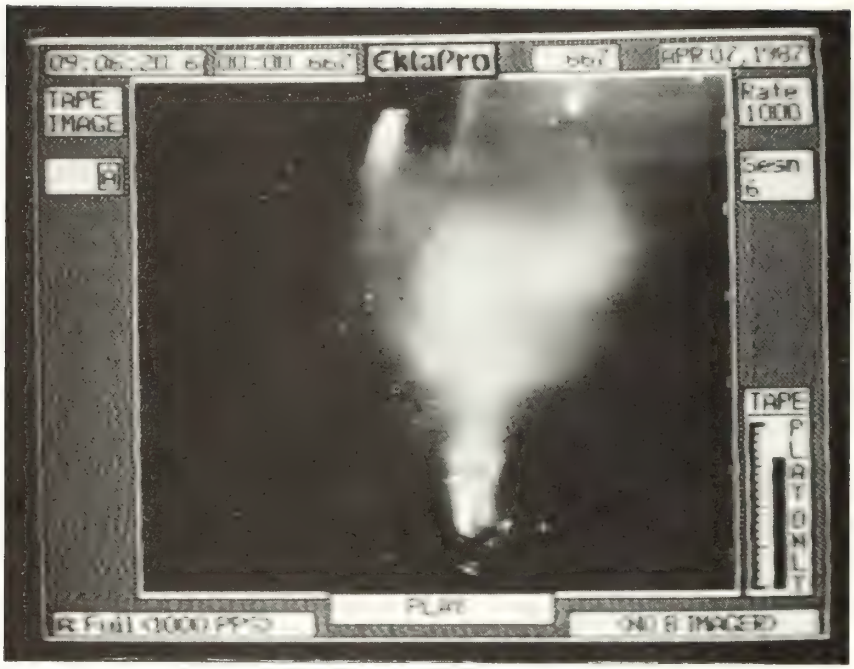
Figure 26—The expanded portion of figure 25, with the apparent angles to the vertical of the anode jet (theta) and cathode jet (beta). The angles were measured from the video records shown in figure 27.

a



b

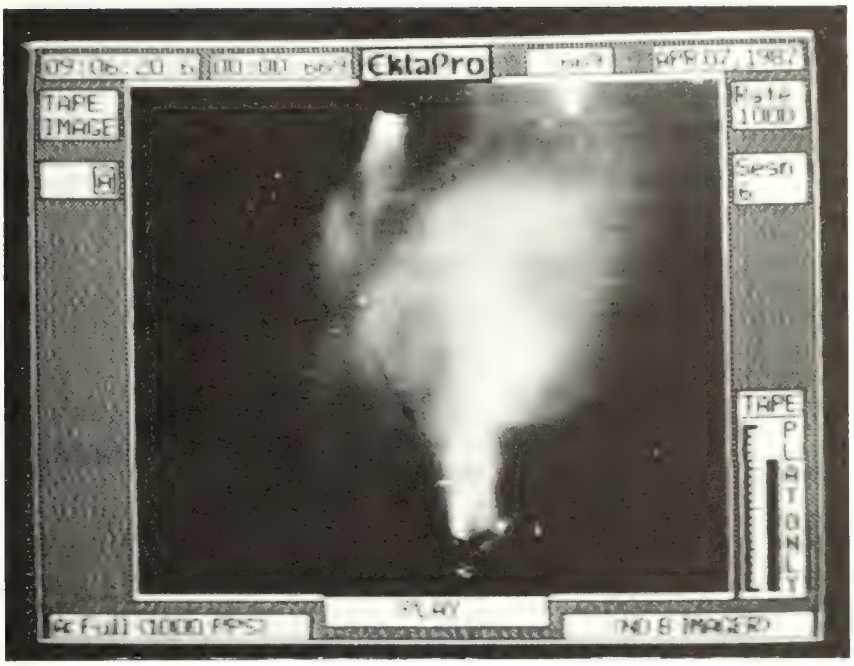
Figure 27—Successive video frames (a-j) of oscillatory arc behavior.



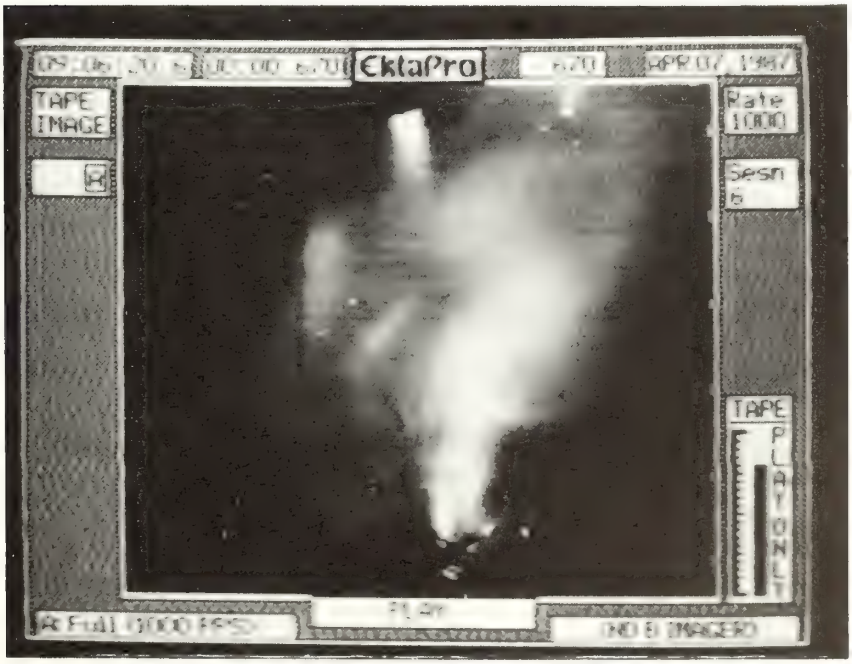
c

d

Figure 27 (Con.)



e



f

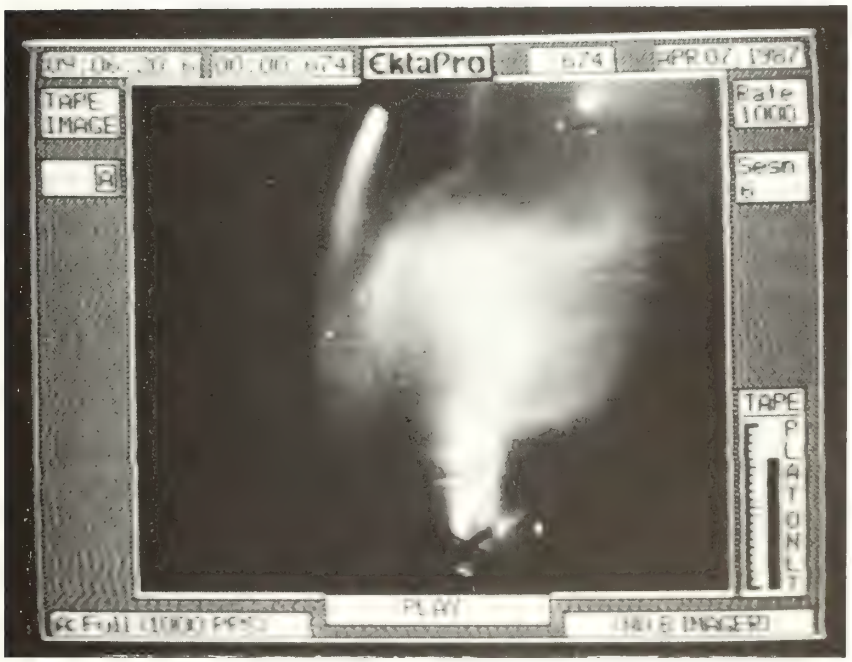
Figure 27 (Con.)

g

h

Figure 27 (Con.)

i



j

Figure 27 (Con.)

clearly show oscillation of the arc anode jet, very likely rotation (an impression from watching the video) about the relatively stable cathode jet. Figure 26 is a time history of the angle of the jets together with the current in the arc. It corresponds to the time period in figure 25 labeled "expanded portion." The jet angle is taken from the video by protractor with respect to the anode-cathode axis. Although anode jet regions are not usually a feature of vertical arcs, they have been observed (Lutz and Pietsch 1980), and look very much like those shown here. Note (Maecker 1971) that the current carrying portion of the arc does not always coincide with the brightest part of the video record, particularly in the diffuse area connecting the cathode and anode jets.

The angular positions of the anode (theta) and cathode (beta) jets with respect to the vertical are shown in figure 26. During this 50 ms of the arc, the anode undergoes about nine oscillations, or a period of about 5.2 ms. Because there is a fuel sample present at the cathode in this arc, the cathode region is seen by the camera to be diffuse. Processing to obtain figures for publication enhances the fuzziness, so that the cathode jet is hidden. In the original videotape the cathode jet is apparent and can be measured. (An unobscured jet can be seen in figure 29a.)

The current trace is also shown on figure 26. Surprisingly, the current is near minimum when the anode jet appears to be closest to the cathode jet, opposite to the condition that might be expected. This is probably an artifact of the two-dimensional view. There is an apparent phase shift as well, perhaps due to the same cause. The current oscillations in this case are about 15 percent of the mean current, as can be seen in figures 25 and 26. Although current records from other arcs show less organized variations in the current, and sometimes greater, the cause of the variations is undoubtedly anode jet wander. High-speed videos of three other arcs, taken on the same day as those of figure 27, verify this view.

We chose one of the other arcs to display the characteristics of the end of the arc time. Figure 28 is the current and light output of a short arc meant to display "shutdown," and figure 29 fast video frames from another arc. Again, we did this to show the light output behavior instead of voltage.

In figure 29, the shutoff of the SCR switch can be clearly seen on the current trace at the end of the 45-ms arc. A large spike is present in all records at shutoff due to commutation of the switch SCR. At shutoff, current flow ceases cleanly, and the gas begins to cool quickly as predicted (Latham 1986). Cooling is also seen in video frames figure 29 b,c,d. Because the arc of figure 29 had no fuel sample present at the cathode, the cathode jet is clearly visible without a haze due to burning material. Note that figure 29a is about 200 ms prior to the remaining frames, which are 1 ms apart and indicate the rapid decay of the hot gas temperature after the current is interrupted.

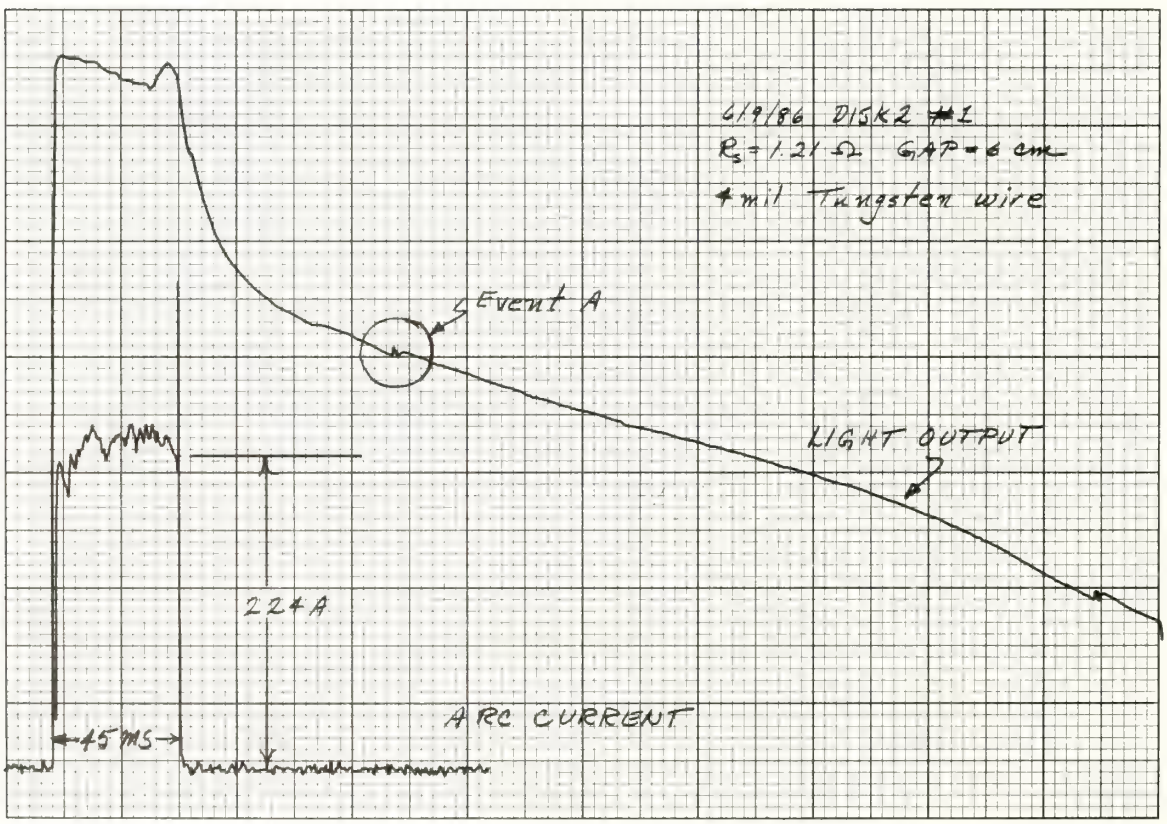
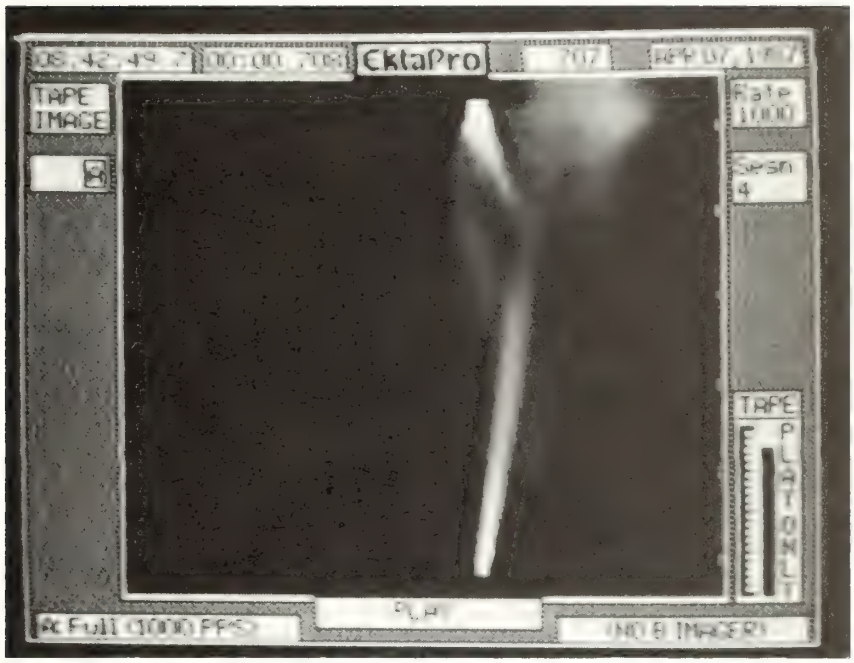
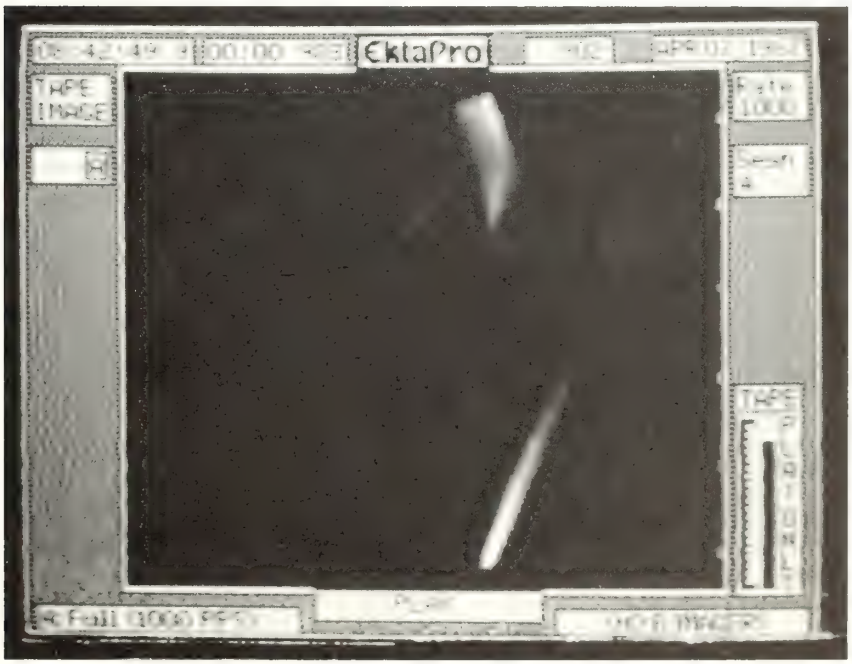


Figure 28—Current and light output records showing arc shut-off.

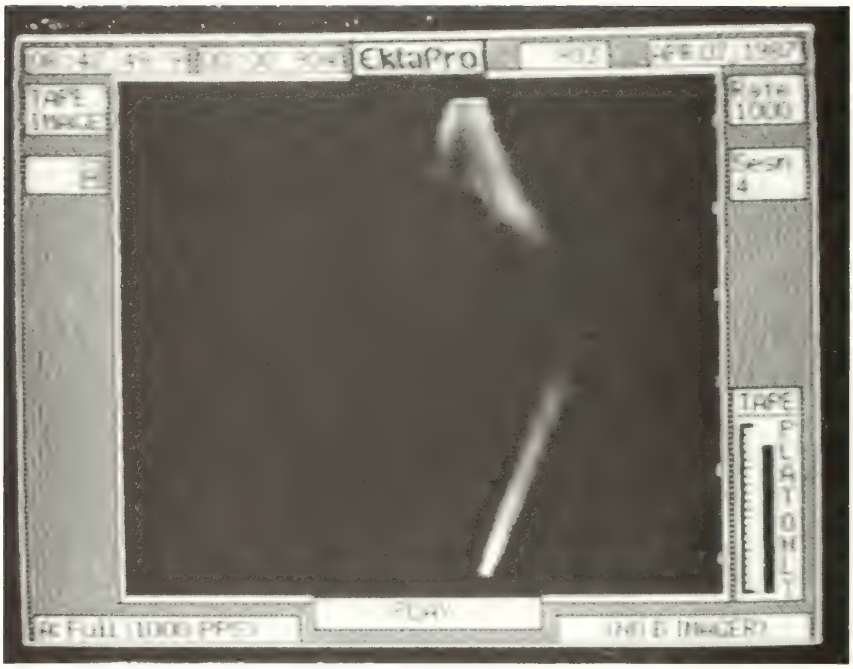


a

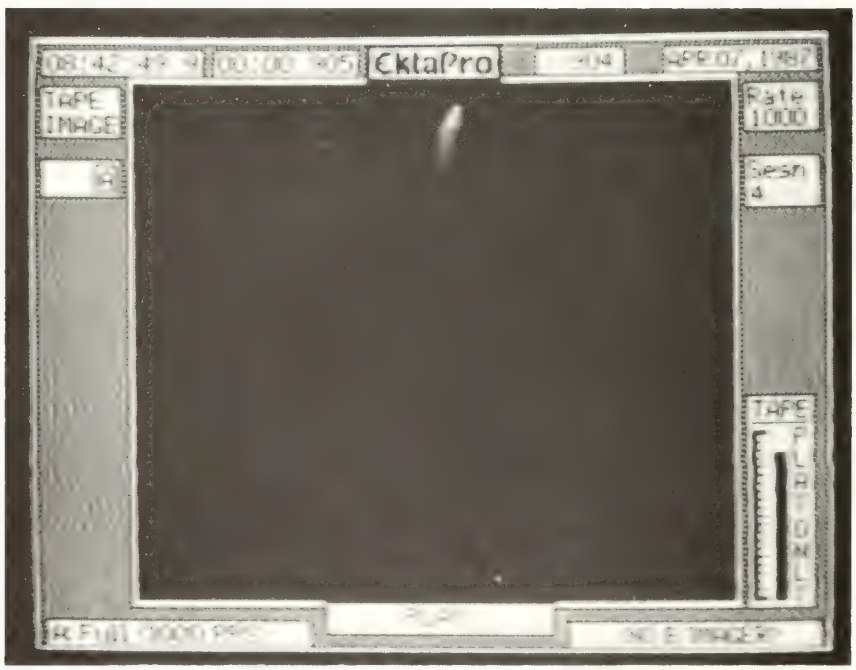


b

Figure 29—A well-formed typical arc; b,c,d: fast video of the shut-off of the same arc.



c



d

Figure 29 (Con.)

The light decay curve, figure 28, has a small variation, labeled Event A. This event occurred in every case looked at with the light sensor. There was no corresponding event in either the voltage or the current. Further, the event was not a constant time after the shutoff pulse, although it seemed to happen at about the same place on the decay curve. We do not know whether this is an electrical artifact, or an event occurring over a very narrow temperature range of the cooling gas, causing a change in emission. An optical spectrometer might provide more information about this event.

SUMMARY AND CONCLUSIONS

The arc behavior has now been described in both gross terms and in time detail. There are many questions raised by even the relatively little fast video data. Due to limitations of time and instrumentation, we will probably not be able to continue the investigation. Nevertheless, we have found that free arcs of the length and current range used in this study have the following characteristics:

- a stable, nearly cylindrical, cathode jet
- a wandering anode jet
- voltage drop dependent only on electrode gap
- current flow dependent only on the electrical source
- gross electrical and cathode jet stability despite flow instabilities
- sufficient predictability and reliability for ignition studies.

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APPENDIX

To do the exploding wire problem in a simple form
using the equivalent circuit of a battery in series
with a current-limiting resistance and the wire.
Assume that all Joule heating stays in the wire.

Battery voltage	V := 500	volts
series resistance	Rs := 1.21	ohms
wire diameter	Dia := .01	cm
wire length	Len := 6	cm
melting point Tungsten	Tf := 3400	deg. C
ambient temperature	To := 20	"

Wire volume

$$vol := \pi \, Len \left[\frac{Dia}{2}\right]^2 \qquad vol = 4.712 \cdot 10^{-4}$$

Wire density rho := 19.3 g/cm^3

Functions:
Specific heat and resistivity of Tungsten:

$$Cp(T) := .13 + 17.2 \cdot 10^{-6} \cdot T \quad \text{joule/g-degC}$$

$$Res(T) := 5.53 \cdot 10^{-6} \cdot (1 + .0045\ T) \quad \text{ohm-cm}$$

The resistance of the wire is thus:

$$Rw(T) := Res(T) \frac{Len^2}{vol} \quad \text{ohms,}$$

the current flow in the circuit is:

$$I(T) := \frac{V}{Rs + Rw(T)}$$, and the power is: $P(T) := I(T)^2 \, Rw(T)$

So, if t is the time taken to reach the melting point of the wire,

$$t(Tf) := \int_{To}^{Tf} rho \, vol \frac{Cp(T)}{P(T)} \, dT \qquad \tau(Tf) := t(Tf) \cdot 10^6$$

For this example, then, $\tau(Tf) = 135.327$ μsec

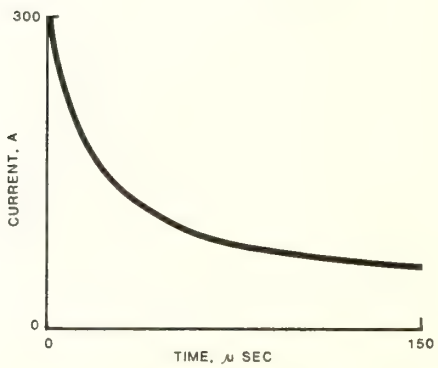
To get the time behavior, set index k := 1 ..170

and define a set of temperatures, $Tv_k := 20\ k$

then if $tim_k := \tau\left[Tv_k\right]$,

and if $cur_k := I\left[Tv_k\right]$,

the following time behavior is obtained:



Latham, Don J. 1989. Characteristics of long vertical DC arc discharges. Res. Pap. INT-407. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 32 p.

Experiments were conducted to ascertain the discharge characteristics of direct-current arcs approximately 10 cm in length, in an effort to estimate the fire-starting potential of lightning and downed powerlines. Vertical arcs of this length were generated by a high-current battery and an SCR switching system. Voltage-current relationships depend on arc length and source conductance. Voltage drop across the arc depends largely on arc length and is independent of the current. Current flow is independent of length, but dependent on source conductance. Arc behavior generally agrees with an earlier theoretical model. High-speed video images of arcs are included in this report.

KEYWORDS: electrical physics, ignition, electrical discharges, lightning

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Responses of Birds and Small Mammals to Single-Tree Selection Logging in Idaho

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CLEMSON

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RESEARCH SUMMARY

Responses of birds and small mammals to logging depend on the cutting methods used and the degree to which forest stands are altered. This study examined short-term changes in the composition and abundance of small mammals and breeding birds following single-tree selection logging in an Idaho Douglas-fir forest. Populations of birds and small mammals were estimated on a logged plot and on a nearby unlogged plot from 1975 (2 years prelogging) to 1979 (3 years postlogging).

Total numbers of breeding birds were relatively stable between years and between logged and unlogged plots. More pronounced patterns of response occurred in the populations making up the breeding bird communities. Species with positive numerical responses to the selection cut were olive-sided flycatcher, Swainson's thrush, yellow-rumped warbler, and chipping sparrow. Species with negative numerical responses to logging were red-breasted nuthatch and brown creeper. Fourteen other species showed little numerical response to the timber harvest.

Birds that forage by gleaning the surface of the bark (timber gleaners) declined in number after logging. Foliage feeders, aerial-sally feeders, and timber drillers were about equally abundant before and after logging. The ground gleaning guild showed a slightly positive pattern of response. Of six nesting guilds represented, only the secondary cavity nesters were adversely affected by logging. Bush and small tree nesters tended to increase after timber harvest.

Deer mice, yellow pine chipmunks, and boreal redback voles accounted for 93 percent of 815 individual animals trapped during the study. Postlogging estimates of deer mice density were generally similar on both the logged and the unlogged plots. But when results were expressed as the mean number of individual animals trapped each year, significantly fewer deer mice were trapped on the logged plot. Numbers of yellow pine chipmunks increased on logged sites; it was the most commonly trapped small mammal in postlogging environments. No significant difference was found in the number of redbacked voles trapped in the cut and uncut forest. Other species were trapped irregularly and in smaller numbers.

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Responses of Birds and Small Mammals to Single-Tree Selection Logging in Idaho

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INTRODUCTION

Alterations in the structure of forest vegetation caused by logging produce changes in the organization of associated bird and small mammal communities. Population responses to logging depend on the cutting methods used and the degree to which stands are altered. The effects of clearcut logging have been extensively reviewed (Blake 1982; Halvorson 1982; Martell 1983; Medin 1985; Scott and others 1982; Szaro and Balda 1979). Populations of some birds and small mammals may increase while others decline in postclearcut environments (Medin 1985, 1986).

Few studies have been conducted on the effects of other methods of tree removal (but see Campbell and Clark 1980; Franzreb and Ohmart 1978; Scott and Gottfried 1983). Alternative cutting methods include the selection method where the oldest or largest trees in a stand are removed either singly (single-tree selection) or in groups (group selection) without completely clearing the entire stand (Smith 1962).

This study, conducted from 1975 to 1979, examined short-term changes in the composition and abundance of small mammals and breeding birds following single-tree selection logging in a Douglas-fir (*Pseudotsuga menziesii)* forest in west-central Idaho. Data were collected as part of a study of the environmental effects of logging and associated road construction in the Idaho batholith, a large region (16,000 mi^2) characterized by steep topography and shallow, erodible soils (Megahan 1983). Selection cutting is one of several timber harvesting methods currently being evaluated for their multiple effects on the forest ecosystem.

Common and scientific names of birds and small mammals referred to in this paper are listed in appendix I.

STUDY AREA

The study was conducted on two experimental watersheds of 319 acres (SC-3) and 67 acres (SC-7) in the Silver Creek drainage, a tributary of the Middle Fork of the Payette River in Valley County, ID. These third-order watersheds range in elevation from 4,600 to 6,500 ft and are representative of forested drainages found in midelevation, nonglaciated landscapes of the Idaho batholith. Slopes are steep and dissected. Watershed SC-3 drains to the southeast; watershed SC-7 drains to the northwest. The area has a Mediterranean climate with hot, dry summers and cool, moist winters. Annual precipitation averages 39 inches, with about 65 percent falling as snow (Megahan and others 1983). High-intensity convective rainstorms are common during the summer months.

Douglas-fir and ponderosa pine (*Pinus ponderosa*) are the dominant overstory trees, with scattered stands of grand fir (*Abies grandis*), lodgepole pine (*Pinus contorta*), and Engelmann spruce (*Picea engelmannii*). Mallow ninebark (*Physocarpus malvaceous*), and white spiraea (*Spiraea betulifolia*) normally dominate the shrubby undergrowth. Rocky Mountain maple (*Acer glabrum*), snowberry (*Symphoricarpos* spp.), common chokecherry (*Prunus virginiana*), blue huckleberry (*Vaccinium globulare*), and western serviceberry (*Amelanchier alnifolia*) are often present. Willows (*Salix* spp.) and alders (*Alnus* spp.) are locally abundant, especially on the north-facing watershed. Many forbs and graminoids occupy the ground layer.

Two main habitat types (Steele and others 1981) occur: Douglas-fir/ninebark, ponderosa pine phase, and Douglas-fir/white spiraea, ponderosa pine phase. The experimental watersheds also include elements of the grand fir/blue huckleberry and subalpine fir (*Abies lasiocarpa*)/blue huckleberry habitat types (Ryker 1973).

LOGGING PROCEDURE

Selected trees in watershed SC-7 were marked and felled within a defined cutting unit boundary. Watershed SC-3 served as a nearby unlogged control. The logged cutting unit was irregularly elongate and followed the topographic boundary of the experimental watershed. Uncut buffer zones bordered stream channels and averaged 50 ft to first-order or second-order stream channels, and 100 ft to the third-order (main) stream channel. Logs were yarded by helicopter to minimize site damage, a common practice on steep slopes in the Idaho batholith. Logging slash was lopped and scattered.

A prelogging timber volume on the cutting unit of 17,087 bd ft per acre was reduced 29 percent by the selection-cut logging. There were 47 trees (>9 inches diameter at breast height) per acre on the watershed before cutting; 38 trees per acre remained after logging (McKenzie 1987). The cutting was originally targeted to reduce prelogging stand volume on the experimental watershed by 30 to 35 percent. Logging began in September and was completed in October 1976.

STUDY METHODS

Bird and small mammal study plots were established on each of the experimental watersheds before logging. Bird and small mammal populations were estimated annually beginning in 1975 (2 years prelogging) and ending in 1979 (3 years postlogging). Trees were harvested on the logged watershed after completion of field work in the autumn of 1976.

Breeding Birds

Two plots of 20 acres each were censused for breeding birds using the Williams spot-map method (International Bird Census Committee 1970). Methodological difficulties and other special problems of the mapping method are summarized by Oelke (1981). Plots were rectangular and varied slightly in shape depending on topography and cutting unit boundaries. Plots were surveyed and gridded in a Cartesian coordinate system with points flagged and numbered with stakes at 164-ft intervals. At least 10 census visits were made annually to each plot from mid-May to late July. Most of the bird registrations were recorded from sunrise to late morning when birds were most active. To ensure complete coverage, the plot was censused by walking within 82 ft of all points on the grid. Observations and registrations extended well beyond plot boundaries. Census routes were varied.

At the end of the sampling period, concentrated groups of registrations and coded activity patterns were circled as indicating areas of activity or approximate territories. Fractional parts of boundary territories were estimated to the nearest one-quarter territory. Results were converted to the number of pairs of breeding birds per 100 acres. Estimates of bird species diversity followed Hill (1973).

Small Mammals

Small mammal populations were estimated on two permanently marked 5.6-acre trapping grids. Grids were located near the center of the larger bird census grids. Each grid measured 495 by 495 ft and consisted of 100 trap positions regularly spaced at 55-ft intervals in 10 rows and 10 columns. One metal Tomahawk live trap, 3 by 3 by 10 inches, was placed near each position. Traps were baited with a mixture of cracked corn, wheat, and rolled oats. Surgical cotton was placed in each trap to minimize death from exposure. Captured animals were ear-tagged with Monel fingerling tags and released at the point of capture. Trapping was conducted annually for a 6-night period on each grid in August and early September.

Populations of the deer mouse, yellow pine chipmunk, and boreal redback vole were estimated by means of the mark-recapture method and the Schnabel estimator (as described in Overton and Davis 1969). The effective trapping area was considered to be the dimensions of the grid plus a strip whose width was equal to half the average range length added to each side. Range length was determined by the "adjusted range length" method described by Stickel (1954).

As an additional indicator of abundance, the number of individual animals caught in each 6-night trapping period was used for deer mice, yellow pine chipmunks, redback voles, shrews, western jumping mice, and the sum of other small mammals that were trapped in small numbers.

Data Analysis

The analysis of breeding bird populations was performed on the differences between corresponding means for the two study plots (that is, the mean of the logged plot minus the mean of the unlogged plot). We felt that the mean level of such differences should have neither an upward nor downward slope during the period prior to logging. Once logging had occurred, an upward slope would indicate that logging had increased the breeding bird density while a downward slope would indicate a decrease. With this in mind, a grafted-polynomial model was fitted to the data. The model assumed a slope of zero for the prelogging period (1975 to 1976) and allows either a negative or positive slope for the three postlogging years (1977 to 1979). The probabilities presented in table 1 test the hypothesis of a change in slope beginning after logging. A small probability, say $P<0.05$, suggests a change in slope.

A contingency table analysis was performed on the number of individual small mammals trapped on logged and unlogged study plots. The chi-square test was designed to detect differences in the pattern of numbers of mammals trapped between the logged and unlogged plots. Although the analysis was based on individual counts rather than means of counts, the means are presented in table 2 to make it easier to see the patterns. The confidence limits presented in figure 1 use calculations for estimates of small mammal population densities given by Overton and Davis (1969).

Because this study was not replicated, it was necessary to make the assumption of independence among yearly observations in order to perform the analyses. Even with this assumption, the tests are not powerful. Therefore, we may have failed to detect some changes that took place (large Type II error), but it is unlikely that the differences we discuss are by chance alone (small Type I error). The assumption of independence from year to year, although not strictly true, is probably inconsequential in view of the rather dramatic postlogging changes in some of the bird and small mammal populations.

Table 1—Density (pairs per 100 acres), diversity, and other attributes of breeding birds on logged and unlogged study plots, west-central Idaho, 1975 to 1979

Species	Feeding guild[1]	Nesting guild[2]	Density										
			Unlogged					Prelogging		Postlogging[3]			
			1975	1976	1977	1978	1979	1975	1976	1977	1978	1979	Probability[4]
Calliope hummingbird	FNI	BTN	3.7	7.5	5.0	7.5	7.5	3.7	6.2	5.0	7.5	8.7	0.099
Hairy woodpecker	TDI	PCN	2.5	2.5	5.0	2.5	5.0	1.2	5.0	2.5	2.5	2.5	.707
Northern flicker	GGI	PCN	3.7	2.5	2.5	2.5	2.5	1.2	2.5	2.5	1.2	2.5	.582
Olive-sided flycatcher	ASI	CTN	0	0	0	0	+[5]	0	+	+	3.7	3.7	.032
Empidonax flycatcher[6]	ASI	BTN	13.7	20.0	20.0	17.5	16.2	31.2	25.0	23.7	27.5	27.5	.973
Mountain chickadee	FGI	SCN	13.7	17.5	18.7	15.0	10.0	12.5	15.0	15.0	12.5	8.7	.528
Red-breasted nuthatch	TGO	SCN	21.2	17.5	15.0	17.5	23.7	20.0	17.5	12.5	8.7	12.5	.004
Brown creeper	TGO	SCN	+	+	6.2	10.0	13.7	8.7	6.2	5.0	7.5	10.0	.035
Winter wren	GGI	GRN	0	0	+	+	0	5.0	0	5.0	8.7	2.5	.668
Golden-crowned kinglet	FGI	CTN	+	3.7	+	2.5	0	5.0	3.7	5.0	3.7	5.0	.707
Ruby-crowned kinglet	FGI	CTN	0	+	0	0	2.5	+	5.0	2.5	2.5	2.5	.490
Townsend's solitaire	FFO	GRN	0	1.2	+	+	0	5.0	3.7	1.2	+	+	.071
Swainson's thrush	FFO	CDN	37.5	25.0	21.2	33.7	26.2	42.5	31.2	33.7	43.7	45.0	.038
Hermit thrush	FFO	BTN	2.5	0	3.7	+	2.5	0	+	+	0	+	.889
American robin	GGI	BTN	7.5	6.2	5.0	5.0	7.5	7.5	2.5	5.0	8.7	5.0	.753
Varied thrush	GGI	BTN	0	+	+	0	0	+	+	2.5	+	0	.891
Solitary vireo	FGI	CDN	5.0	1.2	7.5	7.5	2.5	3.7	7.5	13.7	10.0	10.0	.461
Warbling vireo	FGI	BTN	0	0	0	0	0	0	0	+	+	3.7	.126
Nashville warbler	FGI	GRN	+	3.7	2.5	5.0	3.7	5.0	12.5	16.2	10.0	8.7	.606
Yellow-rumped warbler	FGI	CTN	13.7	13.7	12.5	5.0	2.5	13.7	20.0	18.7	15.0	15.0	.049
Townsend's warbler	FGI	CTN	+	10.0	7.5	+	+	7.5	8.7	11.2	17.5	12.5	.153
MacGillivray's warbler	FGI	BTN	12.5	12.5	13.7	22.5	23.7	13.7	17.5	18.7	21.2	33.7	.528
Western tanager	FGI	CTN	22.5	22.5	17.5	20.0	18.7	20.0	20.0	16.2	16.2	12.5	.092
Black-headed grosbeak	FGI	CDN	0	0	+	0	+	0	2.5	3.7	+	+	.493
Chipping sparrow	GGG	BTN	15.0	22.5	18.7	10.0	10.0	13.7	20.0	18.7	18.7	25.0	.005
Dark-eyed junco	GGG	GRN	20.0	17.5	22.5	16.2	17.5	15.0	17.5	21.2	25.0	17.5	388
Cassin's finch	GGG	CDN	+	5.0	7.5	+	3.7	+	5.0	5.0	5.0	2.5	.800
Pine siskin	FGG	CDN	+	2.5	+	2.5	3.7	5.0	3.7	2.5	5.0	2.5	.199

(con.)

Table 1 (Con.)

Species	Feeding guild[1]	Nesting guild[2]	Density: Unlogged 1975	Unlogged 1976	Unlogged 1977	Unlogged 1978	Unlogged 1979	Prelogging 1975	Prelogging 1976	Postlogging[3] 1977	Postlogging[3] 1978	Postlogging[3] 1979	Probability[4]
Total pairs per 100 acres			194.7	214.7	212.2	202.4	203.3	240.8	258.4	266.9	282.0	279.7	
Total individuals per km²			974	1,074	1,061	1,012	1,016	1,204	1,292	1,334	1,410	1,398	
Standing crop biomass (g per ha)[7]			229	213	216	203	215	234	243	258	268	255	
Species richness (*n*)			15	20	19	18	20	21	23	25	23	24	
Species diversity ($1/\Sigma P_i^2$)			9.9	12.9	13.9	11.5	12.4	11.9	14.7	15.4	14.0	12.8	

[1]After Diem and Zeveloff (1980). FNI=foliage nectivore-insectivore, TDI=timber drilling insectivore, GGI=ground gleaning insectivore, ASI=aerial-sally feeding insectivore, FGI=foliage gleaning insectivore, TGO=timber gleaning omnivore, FFO=foliage feeding omnivore, GGG=ground gleaning granivore, FGG=foliage gleaning granivore.

[2]After Diem and Zeveloff (1980). BTN=bush and small tree nester, PCN=primary cavity nester, CTN=conifer tree nester, SCN=secondary cavity nester, GRN=ground nester, CDN=conifer-deciduous tree nester.

[3]Logging began in September and was completed in October 1976.

[4]Probability associated with the statistical test. A small probability suggests that the change in pattern from the prelogging period to the postlogging period was different on the logged plot than on the unlogged plot. A large probability suggests no evidence for such a difference.

[5]+ indicates that the bird species was observed on a plot, but too infrequently to delineate a territory.

[6]Specific identification of the *Empidonax* flycatcher was not confirmed.

[7]Species weights from Dunning (1984).

Table 2—Mean number of individual animals trapped per year on logged and unlogged study plots, west-central Idaho, 1975 to 1979

Species	Unlogged: Prelogging	Unlogged: Postlogging	Logged: Prelogging	Logged: Postlogging	Probability[1]
Deer mouse	26.0	25.0	43.0	24.0	0.024
Yellow pine chipmunk	31.5	18.7	21.0	36.0	.001
Boreal redback vole	12.0	14.7	19.0	31.7	.329
Shrew	4.0	2.7	5.5	0	.005
Western jumping mouse	0	0	1.5	2.3	—[2]
Others[3]	0.5	1.3	5.0	2.7	.159

[1]Probability that the observed difference in pattern between the logged and unlogged plots could occur by chance alone.

[2]Probability not computed due to failure to trap any animals on the unlogged plot.

[3]Other species include the northern flying squirrel, longtail weasel, northern pocket gopher, and water vole.

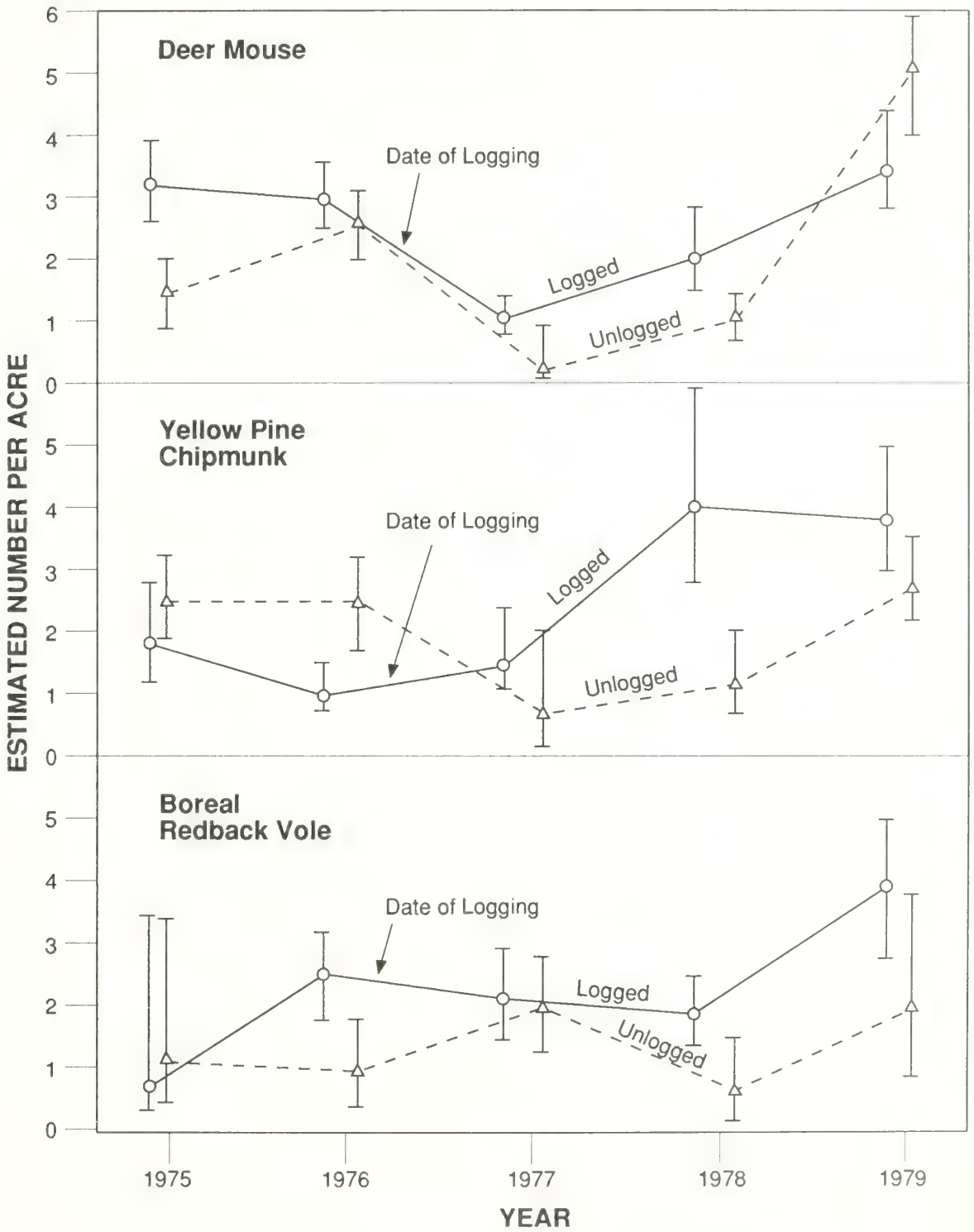

Figure 1—Estimated densities of deer mice, yellow pine chipmunks, and boreal redback voles on logged and unlogged study plots, 1975 to 1979. Confidence limits are at the 95 percent level.

RESULTS: BREEDING BIRDS

Little change occurred in total breeding bird populations as a result of the selection-cut logging (table 1). Prelogging and postlogging estimates of total density, standing crop biomass, and species diversity were similar. All but one of the 28 breeding bird species listed in table 1 were found in both logged and unlogged environments. The olive-sided flycatcher, warbling vireo, and varied thrush were territorial birds only on the logged plot. Numbers of individual species fluctuated widely from year to year on both logged and unlogged plots. Annual fluctuations in total bird populations were less extreme.

The most abundant species in the unlogged forest—each making up more than 5 percent of the breeding bird community and collectively accounting for 77 percent—were:

Empidonax flycatcher
mountain chickadee
red-breasted nuthatch
Swainson's thrush
yellow-rumped warbler
MacGillivray's warbler
western tanager
chipping sparrow
dark-eyed junco

In the logged forest, species each making up more than 5 percent of the breeding bird community and collectively accounting for 65 percent were:

Empidonax flycatcher
Swainson's thrush
yellow-rumped warbler
Townsend's warbler
MacGillivray's warbler
western tanager
chipping sparrow
dark-eyed junco

Among these eight most abundant species, seven were common to both logged and unlogged plots.

Several species responded either positively or negatively to the selection-cut logging (table 1). Species with significant upward patterns of numerical response included the olive-sided flycatcher, Swainson's thrush, yellow-rumped warbler, and chipping sparrow. Of these, only the olive-sided flycatcher nested in the overstory; the others nested either in the midstory or understory layers of vegetation. Olive-sided flycatchers, chipping sparrows, and yellow-rumped warblers have shown positive numerical responses to tree removal treatments elsewhere in western coniferous forests (Medin 1985).

Each of the four species showing a positive response to the logging treatment is classified as having a medium versatility rating with respect to reproduction and feeding orientation, and each is characteristic of shrub-forest ecotonal habitats (Thomas 1979). All but the yellow-rumped warbler are oriented to a variety of successional habitats (Thomas 1979). Each is a common summer resident throughout the coniferous forests of central Idaho (Burleigh 1972).

The warbling vireo, a bird of deciduous shrub and tree habitats (Burleigh 1972), was found as a breeder only on the logged plot. More tall shrubs, particularly willows and alders, were present on the moist sites of the logged watershed. Hermit thrushes, common on the unlogged plot, were not often seen on the logged plot.

The red-breasted nuthatch and the brown creeper responded negatively to the timber harvest (table 1). Both are bark gleaners typically found in late-successional forest habitats (Thomas 1979), and both are secondary cavity nesters. The brown creeper nests under loose bark and is often associated with mature stands of ponderosa pine. The red-breasted nuthatch is a bird of coniferous or mixed coniferous-deciduous forests and may excavate its own nesting cavity if a natural cavity is not available (Burleigh 1972). Both species have low versatility ratings (Thomas 1979). Others (summarized in Medin 1985) have reported similar negative numerical responses by the brown creeper and red-breasted nuthatch to tree removal treatments. The western tanager and Townsend's solitaire showed weaker patterns of decline after timber harvest.

The hairy woodpecker and northern flicker maintained relatively stable densities on both the logged and unlogged plots.

Birds may be placed in categories, or guilds, to organize and compare functional relationships within the community. Guilds were defined by Root (1967) as groups of species that use similar environmental resources in similar ways. The 28 breeding bird species listed in table 1 were organized into feeding and nesting guilds based on their foraging behavior and the substrates used for nesting (table 3).

Birds that feed by searching foliage (foliage feeders and gleaners) formed the largest single feeding guild. These, along with the ground gleaners, made up the largest proportion of all feeding categories. Among the foliage feeders, insectivorous species predominated. The ground gleaners, including chipping sparrows, dark-eyed juncos, and Cassin's finches, were largely granivorous. Two species—the olive-sided flycatcher and the *Empidonax* flycatcher—were classified as aerial-sally feeders. And two species—the red-breasted nuthatch and the brown creeper—were grouped as timber gleaners. The hairy woodpecker was the only timber driller represented.

Foliage feeders, the guild containing the most species, had the highest total density among all feeding or nesting guilds in both the logged and unlogged forest. The Swainson's thrush, western tanager, MacGillivray's warbler, mountain chickadee, and yellow-rumped warbler were the most abundant members of the guild. Of these, only the western tanager declined after logging. Among all feeding guilds, only the timber gleaners were adversely affected by the logging treatment. The negative response of this guild reflects the significant reductions in density of the brown creeper and red-breasted nuthatch, both timber gleaners. Foliage feeders, aerial-sally feeders, and timber drillers were about equally abundant before and after logging. Ground gleaners were slightly more abundant in the logged forest.

Table 3—Guild density (pairs per 100 acres) of breeding birds on logged and unlogged study plots, west-central Idaho, 1975 to 1979

Guild	Density									
	Unlogged					Prelogging		Postlogging[1]		
	1975	1976	1977	1978	1979	1975	1976	1977	1978	1979
Feeding										
Foliage feeders-gleaners	111.1	121.0	109.8	121.2	103.5	137.3	157.2	163.3	164.8	168.5
Aerial-sally feeders	13.7	20.0	20.0	17.5	16.2	31.2	25.0	23.7	31.2	31.2
Timber drillers	2.5	2.5	5.0	2.5	5.0	1.2	5.0	2.5	2.5	2.5
Timber gleaners	21.2	17.5	21.2	27.5	37.4	28.7	23.7	17.5	16.2	22.5
Ground gleaners	46.2	53.7	56.2	33.7	41.2	42.4	47.5	59.9	67.3	55.0
Nesting										
Conifer tree nesters	36.2	49.9	37.5	27.5	23.7	46.2	57.4	53.6	58.6	51.2
Conifer-deciduous tree nesters	42.5	33.7	36.2	43.7	36.1	51.2	49.9	58.6	63.7	60.0
Bush and small tree nesters	54.9	68.7	66.1	62.5	67.4	69.8	71.2	73.6	83.6	103.6
Primary cavity nesters	6.2	5.0	7.5	5.0	7.5	2.4	7.5	5.0	3.7	5.0
Secondary cavity nesters	34.9	35.0	39.9	42.5	47.4	41.2	38.7	32.5	28.7	31.2
Ground nesters	20.0	22.4	25.0	21.2	21.2	30.0	33.7	43.6	43.7	28.7

[1]Logging began in September and was completed in October 1976.

Among the six nesting guilds represented, only the secondary cavity nesters reacted negatively to logging (table 3). Numerically, cavity-nesting species made up 22 percent of the breeding bird community on the unlogged plots compared to 15 percent on the logged plot. Primary cavity nesters had similar densities on both logged and unlogged plots. There was a tendency toward increases in bush and small tree nesters, especially evident in the second and third years after logging.

RESULTS: SMALL MAMMALS

Nine species of small mammals were trapped during the 5-year study (table 2). Deer mice, yellow pine chipmunks, and boreal redback voles accounted for 93 percent of the 815 individual animals trapped. Each of those species was trapped each year on both logged and unlogged plots. No shrews were caught in the logged forest. Western jumping mice were trapped only in the logged watershed. Other species, including the northern flying squirrel, longtail weasel, northern pocket gopher, and water vole, were trapped irregularly and in smaller numbers. There were large differences in the number of small mammals trapped each year in both the logged and unlogged forest.

Deer mouse populations fluctuated irregularly during the study (fig. 1). Estimated densities in the unlogged forest ranged from 0.2 to 5.0 animals per acre. Annual fluctuations were less pronounced in the logged watershed. Deer mouse populations were similar on both logged and unlogged plots during the postlogging period. A different pattern of response is suggested when trapping results are expressed as the mean number of individual animals trapped per year in prelogging and postlogging environments (table 2). Significantly fewer individual deer mice were trapped on the logged plot during the postlogging period.

Studies conducted elsewhere in the West found different patterns of response. Gashwiler (1970), Halvorson (1982), Hooven and Black (1976), Tevis (1956), and Van Horne (1981) found more deer mice on logged areas when compared with nearby unlogged habitats. Yet others reported either similar or higher deer mouse populations in uncut forests when compared with recently logged areas (Harris 1968; Petticrew and Sadleir 1974; Scott and others 1982; Sullivan 1979). Differences in the effect of logging may be partly a result of differences in the amount of cover remaining on logged areas as well as variations in food availability characteristic of early successional stages (Van Horne 1981).

Yellow pine chipmunk populations on the logged area were larger than those of the uncut forest (fig. 1). Logging resulted in a nearly twofold increase in estimated density, reaching a high of 4.1 animals per acre in the second year following logging. The number of individual chipmunks trapped showed a significant pattern of positive response to the timber harvest (table 2). It was the most commonly trapped small mammal in the logged forest. The yellow pine chipmunk is an adaptable species, occupying a variety of forested habitats and a wide range of successional stages (Thomas 1979). It is particularly abundant in open stands of ponderosa pine and Douglas-fir (Rickard 1960).

Annual fluctuations in redback vole populations were less extreme than those of the deer mouse and yellow pine chipmunk (fig. 1). Estimated densities in the unlogged forest ranged from 0.7 to 2.0 animals per acre. Populations on the logged plot were only slightly higher than those on the unlogged plot. No significant difference was found in the number of individual redback voles trapped in the cut and uncut forest (table 2). Conversely, redback voles were not found on a nearby plot when the slash was burned following diameter-cut logging (Medin 1986). Scott and others (1982) reported little difference in the

number of redback voles trapped on logged and unlogged areas in Colorado when the slash was left on the ground. Logged habitats seem to support redback voles only when logs or other debris are present (Tevis 1956; Simons 1985). Redback voles apparently prefer moist habitats with an abundant litter of stumps and rotting logs (Merritt 1981).

Other species of small mammals were either trapped or observed in the Douglas-fir forest. Only a few shrews were caught during the study, and those only in the unlogged forest (table 2). The forest environment was apparently sufficiently altered by the selection cut that it became a less suitable habitat for shrews, at least in the short term. Western jumping mice were trapped only in the moist streamside zones found on the generally north-facing watershed. The species prefers the wet meadows, bogs, and brushy streamsides associated with riparian habitats (Thomas 1979). Incidental numbers of the northern flying squirrel, longtail weasel, water vole, and northern pocket gopher were trapped. Red squirrels were common on both the logged and unlogged plots. The marten was rarely observed and only in the unlogged forest. The trapping methods used are not an effective means of determining the numbers of most of these species.

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APPENDIX I: COMMON AND SCIENTIFIC NAMES OF BIRDS AND SMALL MAMMALS OBSERVED ON THE STUDY AREA

Birds

Turkey vulture	*Cathartes aura*
Sharp-shinned hawk	*Accipiter striatus*
Cooper's hawk	*Accipiter cooperii*
Northern goshawk	*Accipiter gentilis*
Red-tailed hawk	*Buteo jamaicensis*
Golden eagle	*Aquila chrysaetos*
American kestrel	*Falco sparverius*
Spruce grouse	*Dendragapus canadensis*
Blue grouse	*Dendragapus obscurus*
Ruffed grouse	*Bonasa umbellus*
Great horned owl	*Bubo virginianus*
Northern pygmy-owl	*Glaucidium gnoma*
Calliope hummingbird	*Stellula calliope*
Yellow-bellied sapsucker	*Sphyrapicus varius*
Williamson's sapsucker	*Sphyrapicus thyroideus*
Downy woodpecker	*Picoides pubescens*
Hairy woodpecker	*Picoides villosus*
White-headed woodpecker	*Picoides albolarvatus*
Three-toed woodpecker	*Picoides tridactylus*
Black-backed woodpecker	*Picoides arcticus*
Northern flicker	*Colaptes auratus*
Pileated woodpecker	*Dryocopus pileatus*
Olive-sided flycatcher	*Contopus borealis*
Empidonax flycatcher	*Empidonax* spp.
Gray jay	*Perisoreus canadensis*
Steller's jay	*Cyanocitta stelleri*
Clark's nutcracker	*Nucifraga columbiana*
Common raven	*Corvus corax*
Mountain chickadee	*Parus gambeli*
Red-breasted nuthatch	*Sitta canadensis*
White-breasted nuthatch	*Sitta carolinensis*
Brown creeper	*Certhia americana*
Winter wren	*Troglodytes troglodytes*
Golden-crowned kinglet	*Regulus satrapa*
Ruby-crowned kinglet	*Regulus calendula*
Townsend's solitaire	*Myadestes townsendi*
Swainson's thrush	*Catharus ustulatus*
Hermit thrush	*Catharus guttatus*
American robin	*Turdus migratorius*
Varied thrush	*Ixoreus naevius*
Solitary vireo	*Vireo solitarius*
Warbling vireo	*Vireo gilvus*
Nashville warbler	*Vermivora ruficapilla*
Yellow-rumped warbler	*Dendroica coronata*
Townsend's warbler	*Dendroica townsendi*
MacGillivray's warbler	*Oporornis tolmiei*
Western tanager	*Piranga ludoviciana*
Black-headed grosbeak	*Pheucticus melanocephalus*
Chipping sparrow	*Spizella passerina*
Song sparrow	*Melospiza melodia*
Dark-eyed junco	*Junco hyemalis*
Brown-headed cowbird	*Molothrus ater*
Pine grosbeak	*Pinicola enucleator*
Cassin's finch	*Carpodacus cassinii*
Red crossbill	*Loxia curvirostra*
Pine siskin	*Carduelis pinus*
Evening grosbeak	*Coccothraustes vespertinus*

Small Mammals

Shrew	*Sorex* spp.
Yellow pine chipmunk	*Tamias amoenus*
Red squirrel	*Tamiasciurus hudsonicus*
Northern flying squirrel	*Glaucomys sabrinus*
Northern pocket gopher	*Thomomys talpoides*
Deer mouse	*Peromyscus maniculatus*
Boreal redback vole	*Clethrionomys gapperi*
Water vole	*Arvicola richardsoni*
Western jumping mouse	*Zapus princeps*
Marten	*Martes americana*
Longtail weasel	*Mustela frenata*

Medin, Dean E.; Booth, Gordon D. 1989. Responses of birds and small mammals to single-tree selection logging in Idaho. Res. Pap. INT-408. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 11 p.

Short-term changes in small mammal and breeding bird populations following selective logging in an Idaho Douglas-fir forest are quantitatively described. The study, conducted from 1975 to 1979, compared the composition and abundance of birds and small mammals on a logged plot with those on an unlogged plot.

KEYWORDS: *Pseudotsuga menziesii*, helicopter logging, nongame birds, rodents, timber harvesting, wildlife habitat

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September 1989

Influence of Overstory Removal and Western Spruce Budworm Defoliation on Growth of Advance Conifer Regeneration in Montana

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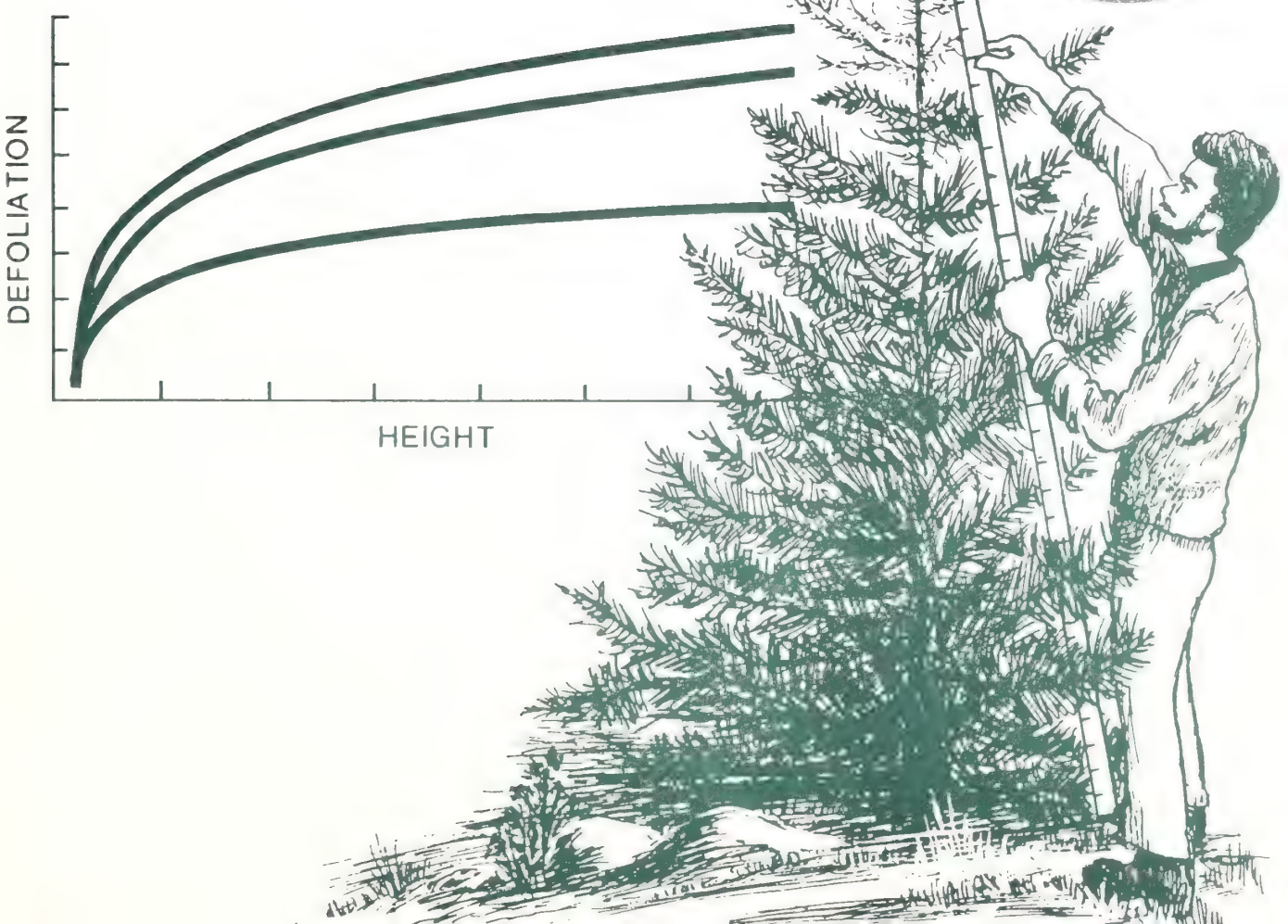

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RESEARCH SUMMARY

The influence of four levels of overstory removal on height and diameter growth of advance regeneration was assessed in larch/Douglas-fir stands in subalpine fir habitat types of northwestern Montana. This study was part of a much larger effort focused on utilization of trees at Coram Experimental Forest. Twelve-year diameter growth of Douglas-fir and Engelmann spruce accelerated with increasing overstory removal, whereas subalpine fir diameter growth increased as the amount of basal area removed increased. Eleven-year height growth of Douglas-fir increased with increasing change in basal area; height growth of subalpine fir increased with both change in basal area and degree of overstory removal. Height growth of spruce increased only with increasing prerelease 10-year radial growth. For Douglas-fir and subalpine fir, height and diameter growth responded to some measure of reduced competition. Nevertheless, radial growth prior to treatment was the variable most indicative of both height and diameter growth of all species. Trees growing well before treatment also grew well following treatment. Mortality was lowest where either all or none of the overstory was removed and was greatest where about 50 percent of the overstory was removed. Western spruce budworm, present in damaging numbers during study establishment, declined soon after harvest and was not present during remeasurement. Defoliation at time of study establishment was greatest on taller trees of all species but significantly affected height growth only of Douglas-fir. Because of the mediocre growth response and the increased susceptibility of such stands to budworm, future volumes in stands composed of and managed for shade-tolerant species may be substantially below volumes expected from stands composed of seral species in these high-quality habitats.

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Influence of Overstory Removal and Western Spruce Budworm Defoliation on Growth of Advance Conifer Regeneration in Montana

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INTRODUCTION

Mature conifer forests in the Northern Rocky Mountains usually have an uneven-aged understory of shade-tolerant conifers, primarily because frequency of surface fires has decreased dramatically since the early 1900's (Arno 1980; Marsden 1983). Larch/Douglas-fir (*Larix occidentalis* Nutt./*Pseudotsuga menziesii* var. *glauca* [Beissn.] Franco) forests on subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.) habitat types (h.t.'s) (Pfister and others 1977) are no exception, usually supporting an extensive understory of subalpine fir, Engelmann spruce (*Picea engelmannii* Parry), and Douglas-fir. These are productive habitat types. Pfister and others (1977) rank *Abies lasiocarpa /Clintonia uniflora* h.t.'s as moderate to highly productive compared to Douglas-fir h.t.'s. Even-aged silviculture often is recommended for these forests, wherein following harvest the advance regeneration is destroyed during site preparation and the stand is subsequently regenerated to seral conifers (Schmidt and others 1983). At times, however, foresters may elect to culture the advance regeneration instead of regenerating a new even-aged stand. Few data exist concerning the performance of advance regeneration after commercial harvest in larch/Douglas-fir forests in the Northern Rockies, and with the current interest in uneven-aged management (implying a significant component of advance shade-tolerant species) it is of considerable interest to know something about its expected growth. Furthermore, western spruce budworm (*Choristoneura occidentalis* Freeman) is present over much of the Northern Rockies (Johnson and Denton 1975), so we also need to understand more about the effects of the insect in stands of advance regeneration.

Research in forest types other than the larch/Douglas-fir in the Western United States indicates that advance regeneration will release after harvest of merchantable trees. In the spruce/fir type, height growth of Engelmann spruce and subalpine fir advance regeneration accelerated following harvest (McCaughey and Schmidt 1982). Regeneration in clearcuts responded better than in partial cuts, whereas understory trees in the controls did not release. Other studies documenting release of conifer advance regeneration in the Western United States following overstory removal include: California red fir (*Abies magnifica* A. Murr.) (Oliver 1986); grand fir (*Abies grandis* [Dougl.] Forbes) (Ferguson and Adams 1980; Seidel 1980); California red fir, white fir (*Abies concolor* [Gord. & Glend.] Lindl.), and Douglas-fir (Helms and Standiford 1985); subalpine fir, white spruce (*Picea glauca* [Moench] Voss), and black spruce (*Picea mariana* [Mill.] B.S.P.) (Johnstone 1978). Most of these studies compared growth prior to clearcutting to postharvest performance rather than investigating effects of overstory removal per se. The purpose of our study was to develop equations to predict postharvest height and diameter growth of advance subalpine fir, Engelmann spruce, and Douglas-fir regeneration in productive subalpine fir habitats and to assess impact of western spruce budworm on the regeneration.

METHODS

Field Study Design

The study was conducted at the Intermountain Research Station's Coram Experimental Forest in northwestern Montana from 1973 to 1984. This study was part of a much larger research and development program dealing with logging systems, utilization, and biological responses (Barger 1980). Elevation in the study area ranges from 4,400 feet mean sea level (m.s.l.) in block 1 to 5,000 feet m.s.l. in block 2. Predominant aspect is east, slopes generally are steep—greater than 50 percent—and annual precipitation is 25 to 35 inches. Habitat type (Pfister and others 1977) over most of the area is *Abies lasiocarpa /Clintonia uniflora* . A western larch/Douglas-fir cover type occupied the area prior to treatment. Stands were two-storied, with dominant and codominant trees averaging about 25 inches diameter breast height (d.b.h.) and 130 feet tall. Average diameter of the understory was about 3 to 4 inches d.b.h. and height about 25 to 35 feet.

Four treatments, randomly assigned within two blocks, were tested: (1) removal of all overstory and all understory trees larger than 7 inches d.b.h.; (2) removal of about 50 percent of the overstory and removal of understory trees larger than 7 inches d.b.h.; (3) removal of all

overstory and understory trees larger than 7 inches d.b.h. in small blocks less than 2 acres in size; and (4) control, where no harvesting was done. Overstory was defined as the canopy stratum that included dominant and codominant trees, whereas understory included all other trees. Unit size for treatments 1 and 2 varied from 3 to 6 acres, and treatments 3 and 4 were about 1.5 acres. Volumes removed in blocks 1 and 2, respectively, were 4,962 and 3,533 ft^3/acre for treatment 1; 2,950 and 2,570 for treatment 2; and 7,655 and 6,241 for treatment 3 (Benson and Gonsior 1981).

Ten 1/50-acre circular plots were systematically established in each treatment, spaced about equally throughout the area. All trees on the plots were numbered with metal tags and measured in 1973, prior to treatment. We remeasured the trees in summer 1985 using the 1984 terminal bud scar as the reference for current height. Thus, the time interval for height growth was 11 years. But because d.b.h. measurements necessarily included 1985 cambial growth, the interval for diameter growth was 12 years. We sampled only the first 10 trees encountered on the plot, beginning at north azimuth and proceeding clockwise, because preliminary data indicated that an adequate sample for assessing growth response could be obtained in this way. Furthermore, in 1985 we sampled only trees not killed or seriously damaged by the logging process because Benson and Gonsior (1981) had already reported on that aspect of the study.

Variables recorded for each tree were:

1. Species.
2. Degree of overstory removal. Coded 1 if partial removal; 2, if total removal on treatment sites greater than 3 acres; 3, if total removal on treatment sites smaller than 3 acres; and 4, for no overstory removal, the control.
3. Total height, to nearest 1 foot.
4. D.b.h., nearest 0.1 inch.
5. Length of live crown, nearest 1 foot.
6. Crown class (dominant, codominant, intermediate, suppressed, or open grown).
7. Mortality not caused by logging.
8. Ten-year radial growth prior to 1973, inch.
9. Percent of foliage removed by western spruce budworm, by crown thirds, visual estimate.

For item 8, increment cores were taken at breast height from plot trees 1 inch d.b.h. and larger to determine age and 10-year radial increment to the nearest 0.0004 inch for the period 1964-73. Smaller trees were a special problem because we felt that extracting a core would alter their growth. And disks could not be taken from the small permanent sample trees because that would have destroyed them. Therefore, we collected disks from small trees (surrogates) nearby, but not within the plots, so we could develop predictive models for prerelease 10-year radial growth of small trees on the permanent plots. Twenty trees each of Douglas-fir, Engelmann spruce, and subalpine fir within each of five height classes were selected without bias. Classes were 0 to 2.0, 2.1 to 3.0, 3.1 to 4.0, and 4.1 to 5.0 feet. Total height and crown length were recorded for each tree. Disks were cut transversely just above the root collar of each tree, placed in plastic bags, and frozen at the end of each field day. Ten-year radial increment was measured in the laboratory to the nearest 0.0004 inch.

DATA ANALYSIS

We used multiple linear regression analyses to develop predictive models for 11-year height and 12-year diameter growth and to test statistical significance of independent variables. If needed, data were transformed to meet assumptions underlying regression analysis. All variables except degree of overstory removal were continuous; dummy variables were created for the categories of this variable. Variables were deemed significant at $P \leq 0.05$. Similarly, the influence of tree and plot variables on defoliation by budworm was tested using multiple linear regression procedures. Multiple linear regression was performed on the data from the small surrogate trees, using 10-year radial growth as the dependent variable and height and crown length as independent variables. Separate regressions were developed for each species. Missing values for small trees on the permanent plots were then computed using coefficients developed in the regressions. Mortality was analyzed using a linear modeling procedure for categorical data (Grizzle and others 1969). All data management and analyses were done with SAS procedures (SAS Institute 1985).

RESULTS

Height Growth

Degree of overstory removal had no effect on post-release height growth of advance Douglas-fir regeneration, but increasing change in basal area had a positive influence, reflecting the release from competition. Basic statistics for all variables are given in table 1 and regression models for estimating 10-year prerelease radial growth for small trees are presented in table 2. (Height and crown length were significant predictors ($P \leq 0.05$) of prerelease radial growth for all three species.) Tree age was not used in any of the analyses because the data had been misplaced and could not be recovered. The natural log of postrelease 11-year height growth was directly related to 10-year radial increment prior to treatment (table 3); height growth increased with larger radial growth (fig. 1). Defoliation by western spruce budworm tended to depress height growth of Douglas-fir. Figure 2 shows the combined effects of prerelease radial growth and defoliation on postrelease height growth, and figure 3 shows the influence of change in plot basal area. The height growth model for Douglas-fir was not very strong; the coefficient of multiple determination (CD) was only 0.20.

Postrelease height growth of Engelmann spruce increased with increasing prerelease radial growth (CD = 0.15), but none of the other variables tested exerted a significant influence (table 3, fig. 1).

Table 1—Means, standard deviations, and sample sizes of variables used in the regression analyses of 11-year height growth, 12-year diameter growth, and budworm defoliation of Douglas-fir, subalpine fir, and Engelmann spruce

Variable	n	Mean	Standard deviation
	Douglas-fir		
Natural log height growth	160	0.275	1.533
Natural log d.b.h. growth	160	–.657	.914
Overstory removal 1	160	.206	.405
Overstory removal 2	160	.188	.392
Overstory removal 3	160	.075	.264
1973 height, feet	160	15.256	13.111
1973 d.b.h., inch	160	2.052	1.992
Crown ratio	160	.497	.251
Plot basal area, ft²	160	1.702	1.653
Basal area change, ft²	160	.950	1.500
10-year radial growth, inch	147	.144	.098
Percent defoliation	140	31.536	27.423
Coefficient variable height	147	103.565	55.139
	Engelmann Spruce		
Natural log height growth	84	0.675	1.623
Natural log d.b.h. growth	84	–.420	.843
Overstory removal 1	84	.321	.470
Overstory removal 2	84	.060	.238
Overstory removal 3	84	.143	.352
1973 height, feet	84	15.643	14.097
1973 d.b.h., inch	84	2.256	2.117
Crown ratio	84	.553	.226
Plot basal area, ft²	84	2.105	2.088
Basal area change, ft²	84	1.399	2.166
10-year radial growth, inch	72	.179	.159
Percent defoliation	69	51.638	28.369
Coefficient variable height	72	95.083	34.259
	Subalpine Fir		
Natural log height growth	229	0.240	1.553
Natural log d.b.h. growth	229	–.961	1.037
Overstory removal 1	229	.114	.318
Overstory removal 2	229	.183	.388
Overstory removal 3	229	.183	.388
1973 height, feet	229	7.039	10.928
1973 d.b.h., inch	229	.833	1.600
Crown ratio	229	.701	.287
Plot basal area, ft²	229	1.667	1.986
Basal area change, ft²	229	1.099	1.701
10-year radial growth, inch	229	.122	.116
Percent defoliation	217	35.083	28.631
Coefficient variable height	221	144.624	60.979

Table 2—Regression models for predicting prerelease 10-year radial growth (inch) of trees less than 1.0 inch d.b.h.

Variable	Coefficient	T	Probability
	Douglas-fir		
Height	–0.004	–1.02	0.309
Crown length	.051	5.91	0
Intercept	.039	2.95	.004
R-square	0.47		
Error mean square	.01		
F for model (Probability)	42.92(0)		
	Engelmann Spruce		
Height	–0.038	–4.59	0
Crown length	.096	8.96	0
Intercept	.043	2.42	.018
R-square	0.62		
Error mean square	.01		
F for model (Probability)	76.35		
	Subalpine Fir		
Height	–0.016	–1.28	0.203
Crown length	.079	5.30	0
Intercept	–.001	–.06	.949
R-square	0.69		
Error mean square	.01		
F for model (Probability)	103.41		

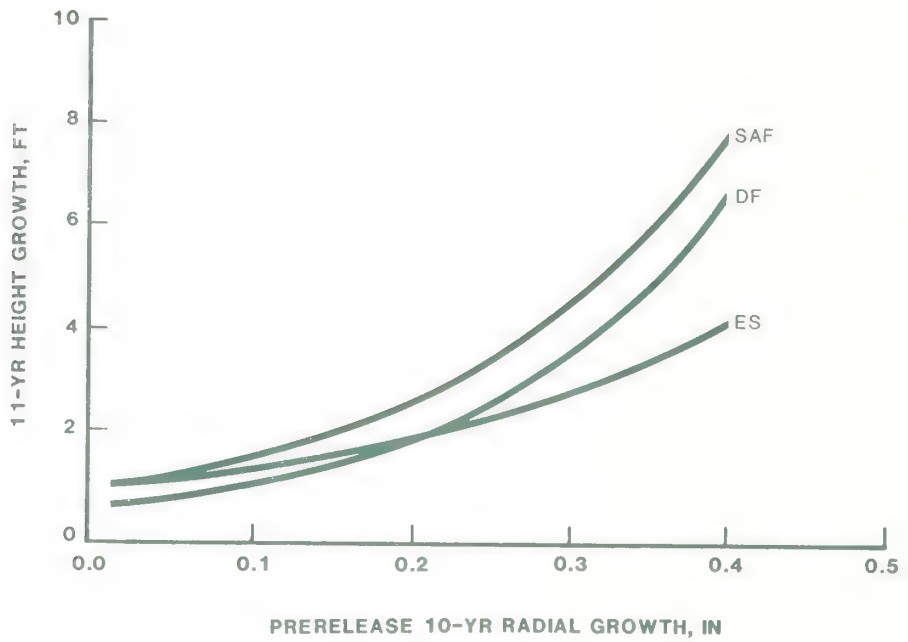

Figure 1—Relationship of 11-year postrelease height growth of subalpine fir, Douglas-fir, and Engelmann spruce to 10-year prerelease radial growth.

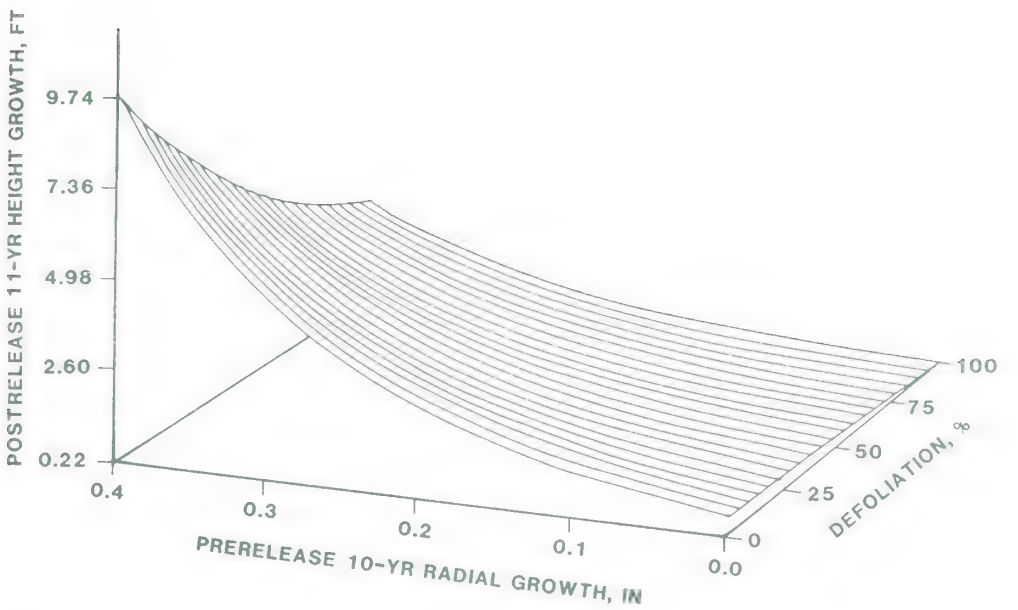

Figure 2—Relationship of 11-year postrelease height growth of Douglas-fir to 10-year prerelease radial growth and western spruce budworm defoliation.

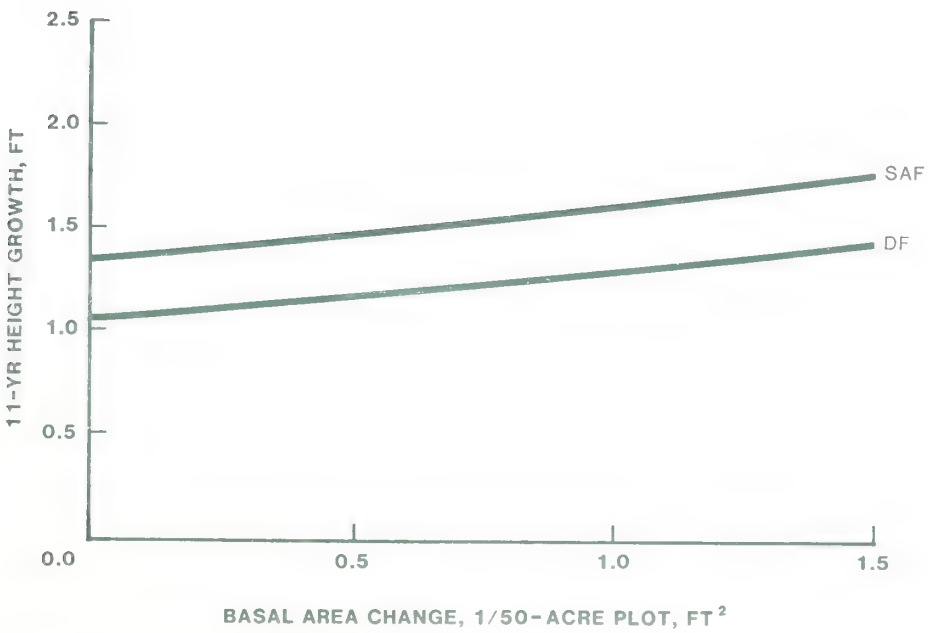

Figure 3—Effect of change in plot basal area on 11-year postrelease height growth of Douglas-fir and subalpine fir.

Height growth of subalpine fir was influenced by degree of overstory removal and several other variables. Trees grew best when all the overstory was removed but grew least in the control and partial removal. Increasing basal area change and prerelease diameter growth also resulted in better height growth (figs. 1, 3). We did not detect a significant influence of budworm on subalpine fir height growth (table 3). This was the strongest height growth model; even so, the CD was only 0.27.

Diameter Growth

Models for predicting 12-year postrelease diameter growth were much stronger than for height growth and showed the release from competition. Ten-year radial growth preceding treatment (fig. 4), d.b.h. at time of treatment, and degree of overstory removal were significant in the model developed for Douglas-fir (table 4) and the CD was 0.53, far larger than for the height growth model of this species. Larger, faster-growing trees where all the overstory was removed grew best. Budworm had no detectable influence.

Posttreatment diameter growth of Engelmann spruce increased with increasing prerelease radial growth and degree of overstory removal (table 4, fig. 4). We did not detect any influence of basal area change, budworm, or other variables tested. The CD for spruce was 0.45, also much larger than for the height growth model.

Diameter growth of subalpine fir responded positively to increasing basal area change and 10-year prerelease radial growth (table 4, fig. 4). The coefficient of multiple determination was 0.50. Oddly enough, trees with smaller crown ratios responded better than those with larger crown ratios. Degree of overstory removal had no influence on diameter growth. Again, budworm did not significantly influence postrelease diameter growth of this species.

Mortality

Chi-square tests indicated that cutting type and species significantly influenced postharvest mortality (table 5). The interaction was nonsignificant. Percent mortality for all species combined, since the study began in 1973, was nearly the same—13 to 14 percent—among the complete overstory removal and control treatments (table 6). In the partial removal, however, mortality was substantially greater—about 25 percent. Among species, mortality was highest for Douglas-fir at 22 percent but about 13 percent for the subalpine fir and spruce. Average mortality over all species and treatments was about 16 percent for the 12-year period, or 1.3 percent per year.

Table 3—Regression equations predicting natural log of 11-year post release height growth of Douglas-fir, Engelmann spruce, and subalpine fir

Variable	Coefficient		T	Probability
		Douglas-fir		
Basal area change	0.210		2.81	0.006
10-year radial growth	6.437		5.10	0
WSB defoliation	–.012		–2.69	.008
Intercept	–.498		–2.02	.050
R-square		0.20		
Error mean square		1.83		
F for regression (Probability)		11.11(0)		
		Engelmann Spruce		
Basal area change	—		—	—
10-year radial growth	3.972		3.38	0.001
WSB defoliation	—		—	—
Intercept	–.171		–60	.545
R-square		0.15		
Error mean square		2.37		
F for regression (Probability)		12.37(0)		
		Subalpine Fir		
10-year radial growth	5.562		6.96	0
Basal area change	.187		2.35	.020
Overstory removal 1	–.372		–1.16	.248
Overstory removal 2	.692		2.37	.019
Overstory removal 3	445		1.34	.182
Intercept	–.826		–5.13	0
R-square		0.27		
Error mean square		1.82		
F for regression (Probability)		15.85		

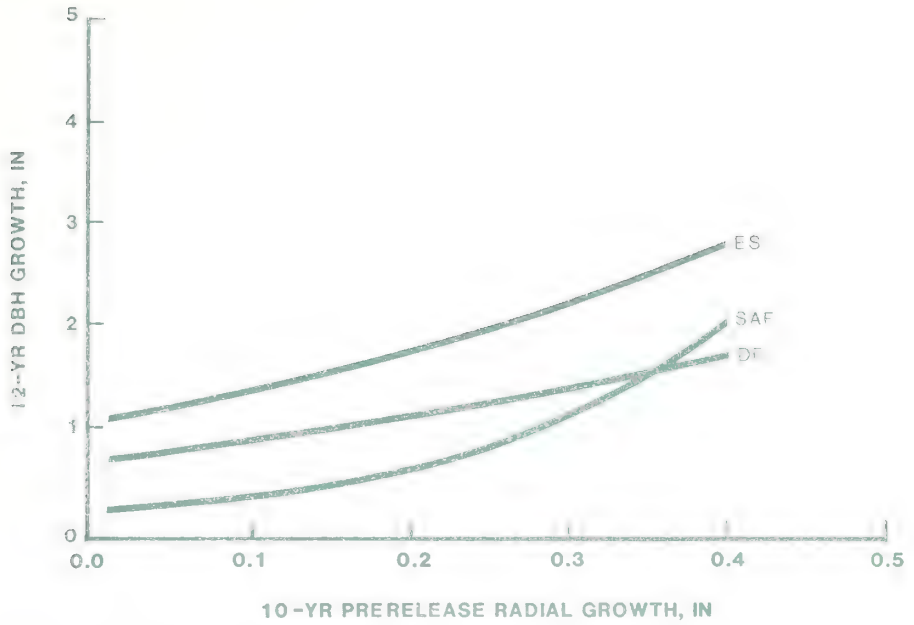

Figure 4—Relationship of 12-year postrelease diameter growth of Douglas-fir, subalpine fir, and Engelmann spruce to 10-year prerelease radial growth.

Table 4—Regression equations predicting natural log of 12-year post release d.b.h. growth of Douglas-fir, Engelmann spruce, and subalpine fir

Variable	Coefficient	T	Probability
	Douglas-fir		
1973 d.b.h.	0.216	6.51	0
10-year radial growth	2.284	3.37	0
Overstory removal 1	.273	2.01	.025
Overstory removal 2	.657	4.54	0
Overstory removal 3	.850	4.22	0
Intercept	–1.685	–15.44	0
R-square	0.53		
Error mean square	.41		
F for regression (Probability)	32.38(0)		
	Engelmann Spruce		
1973 d.b.h.	—	—	—
10-year radial growth	2.453	5.02	0
Overstory removal 1	.359	2.18	.033
Overstory removal 2	1.239	3.68	0
Overstory removal 3	1.277	5.43	0
Intercept	–1.242	–8.29	0
R-square	0.45		
Error mean square	.39		
F for regression (Probability)	13.73(0)		
	Subalpine Fir		
Crown ratio	–0.408	–2.37	0.019
Basal area change	.175	5.67	0
10-year radial growth	6.067	13.89	0
Intercept	–1.629	–11.42	0
R-square	0.50		
Error mean square	.55		
F for regression (Probability)	71.17(0)		

Table 5—Analysis of variance of mortality data

Source of variation	Degrees of freedom	Chi-square	Probability
Intercept	1	133.00	0.0001
Cutting type	3	7.87	.0487
Species	2	6.70	.0351

Table 6—Influence of overstory removal and species on mortality of advance regeneration

Species	Degree of overstory removal				
	Complete, larger units	Complete, smaller units	Partial	Control	Total
	Percent (number)				
Douglas-fir					
Died after 1973	36.8(7)	18.9(7)	32.6(16)	15.0(15)	21.9(45)
Live in 1985	63.2(12)	81.1(30)	67.4(33)	85.0(85)	78.1(160)
Total	100.0(19)	100.0(37)	100.0(49)	100.0(100)	100.0(205)
Engelmann spruce					
Died after 1973	7.7(1)	0(0)	22.9(8)	9.1(4)	13.4(13)
Live in 1985	92.3(12)	100.0(5)	77.1(27)	90.9(40)	86.6(84)
Total	100.0(13)	100.0(5)	100.0(35)	100.0(44)	100.0(97)
Subalpine fir					
Died after 1973	10.6(5)	10.6(5)	16.1(5)	14.4(20)	13.3(35)
Live in 1985	89.4(42)	89.4(42)	83.9(26)	85.6(119)	86.7(229)
Total	100.0(47)	100.0(47)	100.0(31)	100.0(139)	100.0(264)
All species					
Died after 1973	16.5(13)	13.5(12)	25.2(29)	13.8(39)	16.4(93)
Live in 1985	83.5(66)	86.5(77)	74.8(86)	86.2(244)	83.6(473)
Total	100.0(79)	100.0(89)	100.0(128)	100.0(283)	100.0(566)

Table 7—Regression equations for predicting mean percent defoliation caused by western spruce budworm on Douglas-fir, Engelmann spruce, and subalpine fir

Variable	Coefficient		T	Probability
	Douglas-fir			
Natural log 1973 height	8.912		4.12	0
Coefficient variation height	.094		1.98	0.050
Crown ratio	–20.251		–2.02	.045
Intercept	13.320		1.38	.170
R-square		0.20		
Error mean square		618.50		
F for regression (Probability)		11.00(0)		
	Engelmann Spruce			
Natural log 1973 height	16.138		4.86	0
Coefficient variation height	—		—	—
Crown ratio	—		—	—
Intercept	11.047		1.25	.217
R-square		0.26		
Error mean square		603.64		
F for regression (Probability)		23.65(0)		
	Subalpine Fir			
Natural log 1973 height	17.368		8.35	0
Coefficient variation height	–.072		–2.77	0.006
10-year radial growth	–42.256		–2.13	.034
Crown ratio	—		—	—
Intercept	30.188		4.82	0
R-square		0.42		
Error mean square		491.25		
F for regression (Probability)		49.15(0)		

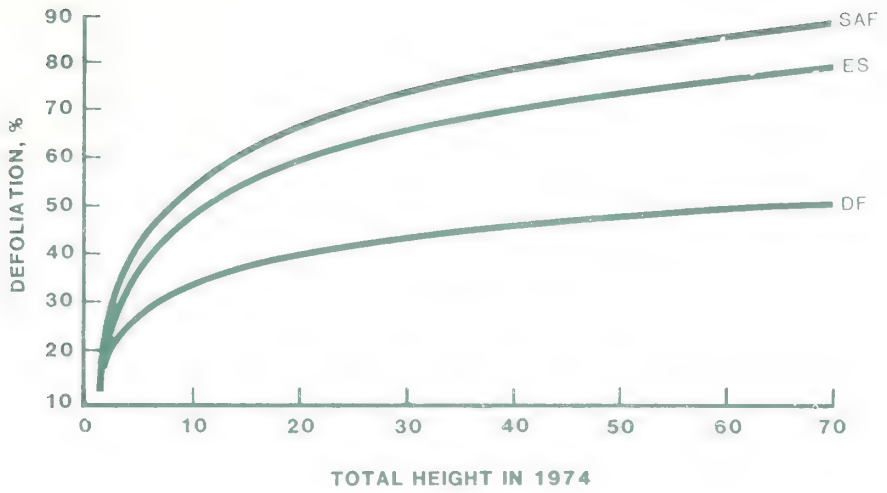

Figure 5—Influence of tree height on western spruce budworm defoliation of Douglas-fir, subalpine fir, and Engelman spruce.

Defoliation

Defoliation in 1973 by western spruce budworm was significantly related to the natural log and the coefficient of variation (cv) of initial height, most strongly for subalpine fir (table 7). Taller trees sustained more defoliation than smaller ones. Higher cv of Douglas-fir height resulted in slightly increased defoliation, whereas the opposite was true for subalpine fir. The only important independent variable influencing defoliation of Engelmann spruce was natural log of initial height. The coefficient of determination was highest for subalpine fir (0.42) and lowest for Douglas-fir (0.20). Percentage of defoliation is shown as a function of tree height for the three species (fig. 5).

DISCUSSION

Height and/or diameter growth of all species increased following treatment and were directly related ($P \leq 0.05$) to at least one of the variables representing competition—degree of overstory removal or change in plot basal area. Change in plot basal area was calculated as the difference between pretreatment and posttreatment basal area; therefore larger values in basal area change represent decreasing competition. Degree of overstory removal also represents decreasing competition. Some of the overstory basal area was included in the calculation of basal area change when an overstory tree occurred on a plot. Thus, the separation of degree of competition due to plot basal area change or degree of overstory removal was not always clear. So both variables need to be considered as measures of stand competition.

In this respect, the results are sensible. Height growth of Douglas-fir increased with increasing change in plot basal area; height growth of subalpine fir increased with change in basal area and degree of overstory removal (table 3). Engelmann spruce height growth did not respond to either measure of competition, however. McCaughey and Schmidt (1982) showed that subalpine fir tended to release more than spruce, although in their study spruce released only minimally. Diameter growth of all three species increased with decreasing competition. Douglas-fir and Engelmann spruce grew faster as degree of overstory removal increased, whereas subalpine fir responded to increasing change in plot basal area (table 4).

Crown ratio was a significant predictor of postrelease d.b.h. growth of subalpine fir. But the sign of the coefficient was opposite of the expected positive relation; better crown ratios were associated with poorer growth. This anomaly remains unexplained. In spite of the statistical significance, this variable added little to the prediction of height growth. A 50 percent change in crown ratio resulted in only about 1.2 feet of height growth over 11 years.

There was little physical difference between the complete overstory removal on "large" units and complete removal on "small" units. The former were 3 to 5 acres, the latter were about 2 acres and in reality should have been considered identical treatments. This lack of real difference is reflected in the regression models for height and diameter growth. Where degree of overstory removal was statistically important, the coefficients representing both categories of complete removal were similar in size to each other but were quite different from the coefficient representing the partial removal. But because the original study had broader objectives than reported here (Barger 1980), we chose to keep the treatments separate.

Notwithstanding the above discussion on the effect of reduced stand competition on tree growth, the variable exerting the most influence on posttreatment height and diameter growth was radial growth prior to treatment (figs. 1, 4). Trees that were vigorous prior to treatment, for whatever reasons, simply outperformed other trees following treatment. This variable was significant in height and diameter models for all three species.

Initial height was not an important predictor in any of our models. Tall trees responded about as well as short ones. Other researchers obtained somewhat different

results. McCaughey and Schmidt (1982) demonstrated that taller (older) Engelmann spruce and subalpine fir responded slower to release than shorter (younger) trees. Taller suppressed grand fir did not release as well as shorter trees of equal suppression, and younger trees released better than older ones (Ferguson and Adams 1980). Initial diameter in our study was important only in the Douglas-fir model, where larger-diameter trees grew faster than the smaller ones.

Tree age was not used as an independent variable in our study. Unfortunately, much of the age data taken in 1974 was lost and sample size of trees for which ages were available was too small for age to be of use in the analyses. Age was an important variable in several previous studies on release of understory (Ferguson and Adams 1980; McCaughey and Schmidt 1982), and we regret the omission of this variable in our analyses. Plot trees will be remeasured in 1994 when we plan to destructively sample, so age will be determined then and included in subsequent analyses. We did not extract increment cores or disks during the 1985 remeasurement because we did not want to jeopardize future growth of the plot trees.

Trees usually do not respond to reduced competition for 3 or 4 years after treatment. Because we used height and diameter growth as dependent variables over the entire period since cutting, the responses may be conservative. Perhaps we should have used only the most current 5-year height and diameter growth as dependent variables. Such data were not taken during this measurement but will be in 1994. Thus, we expect that the future models will be improvements over the current ones.

Even though most studies on release of advance regeneration report significant increases in height and diameter growth following harvest, the absolute growth is small—usually less than 0.5 foot per year for height and less than 0.2 inch per year for diameter growth during the release period even on productive sites. We looked at results from several different studies done in the Western United States (table 8). (See appendix for notes on how table 8 was derived.) Data selected for inclusion in table 8 represent trees of moderate to good vigor, with crown ratios greater than 50 percent—in other words, the better trees left after harvest. In comparison, good-vigor western larch under even-aged management on average sites will grow about 1 foot in height and 0.28 inch per year in diameter during the first 20 years of growth (Schmidt and others 1976).

Predictive value of most models dealing with postharvest release of residual trees is relatively low, even though the models are statistically significant (table 8). Our models are no exception; coefficients of multiple determination for height growth ranged from 0.15 for Engelmann spruce and 0.20 for Douglas-fir to 0.27 for subalpine fir. CD's for diameter growth were higher, ranging from 0.46 for Engelmann spruce and 0.50 for subalpine fir to 0.53 for Douglas-fir in our studies. Similarly, predictive value was not very strong for most of the models developed from other studies on advance regeneration. Coefficients of determination developed by Seidel (1980) ranged from 23.0 to 44.1 for diameter growth and 17.5 to 44.2 for height growth; he did not consider them reliable. Oliver's

Table 8—Height and diameter growth of advance regeneration following harvest, according to several western North American studies

Study/location	Species	Mean annual height growth		Mean annual diameter growth	
		Preharvest	Postharvest	Preharvest	Postharvest
		Feet		*Inches*	
Current/ NW Montana	Subalpine fir	0.10	0.45	0.04	0.04
	Engelmann spruce	.16	.16	.04	.15
	Douglas-fir	.12	.12	.04	.09
Johnstone (1978)/ Alberta, Canada	Subalpine fir	.20	.52	NA	NA
	Spruce	.22	.40	NA	NA
Seidel (1980)/Oregon	Grand fir	.21	.18	.05	.15
Ferguson and Adams (1980)/Idaho	Grand fir	.13	.42	NA	NA
McCaughey and Schmidt (1982)/Utah	Engelmann spruce	.10	.50	NA	NA
	Subalpine fir	.17	.58	NA	NA
Helms and Standiford (1985)/California	White fir	.46	.82	NA	.24
Oliver (1986)/California	Red fir	.46	.29	NA	.15

(1986) models also did not adequately explain the variation in growth of red fir. His best equations, developed for the 2-year period just after thinning, explained less than two-thirds of the variation. Equations for 8 years following treatment had CD's of only 0.33 for diameter growth and 0.24 for height growth. Other CD's reported for height growth were: 0.35 (Ferguson and Adams 1980); 0.11 to 0.58 (McCaughey and Schmidt 1982); 0.56 (Helms and Standiford 1985). The highest CD's developed were 0.77 for subalpine fir and 0.72 for spruce height growth in Alberta, Canada (Johnstone 1978). Models for diameter growth generally had higher predictive power than those for height, supporting our findings at Coram. Comparison of CD's across all studies may not be entirely valid because the nature of the dependent variable differed among studies. Nevertheless, the mediocre CD's simply reflect the inherent difficulty in identifying and measuring key factors affecting tree growth in the field. The models reported in the literature are generally state of the art and are likely about the best that can be expected.

Mortality and serious damage caused by logging in our study area were reported earlier (Benson and Gonsior 1981) so we did not include this type of damage in the present study, except that we included mortality caused by logging as part of the basal area change. They reported that more than 40 percent of the trees were either killed or seriously damaged during the harvesting process in the treatments where all the overstory was removed and about 30 percent where only part of the overstory was removed. We documented only mortality that was not obviously caused at the time of harvest. Mortality of advance regeneration less than or equal to 7 inches d.b.h. was least in the complete overstory removal treatments and controls (13 percent) and greatest in the partial removal (25 percent), amounting to about 1 to 2 percent per year, respectively. Among species, a higher proportion of Douglas-fir (22 percent) died than of Engelmann spruce and subalpine fir (13 percent). We do not know why mortality was greater in the partial removals nor why a higher proportion of Douglas-fir died than the other species. Perhaps root diseases were more active, but this presumption is highly speculative. About all we can say is that our mortality rates are, in a general sense, similar to those predicted by Hamilton (1986) for stands in northern Idaho. He predicted 10-year mortality rates of 0.13 in thinned and nonthinned stands on productive sites in northern Idaho, which translates to 1.3 percent per year.

A serious consequence of leaving advance conifer regeneration in the Northern Rocky Mountains is an increase in stand susceptibility to western spruce budworm. Western larch and Douglas-fir when seral tend not to support populations of the insect (Carlson and others 1985). Stands dominated by subalpine fir, Engelmann spruce, and/or grand fir in the overstory or understory are highly susceptible. Two to three years prior to and during establishment of this study in 1973, budworm was active and moderate in the study area; 30 to 50 percent defoliation was present on the advance regeneration. Subalpine fir and Engelmann spruce sustained more defoliation than Douglas-fir. This supports other observations we have made; when Douglas-fir is seral it tends to have less defoliation than its more shade-tolerant associates (Carlson and others 1985). We thought this situation would provide an excellent opportunity to assess differential effects of the insect on advance regeneration. But for unknown reasons, budworm nearly disappeared from the study area after 1975, and we ended up with only 1 year's defoliation data. Even so, we did find a significant effect of defoliation on one species. Increasing defoliation was associated with decreasing height growth of Douglas-fir (fig. 2).

Other studies concerning the influence of defoliation on tree growth support these results. Ferguson (1988) demonstrated that probability of top dieback increased with increasing defoliation, and that periodic height increment was reduced. His study specifically considered defoliation over a 5-year period—longer than our outbreak. Furthermore, at the time he selected his stands, the budworm outbreak was in progress, therefore his sample trees likely were defoliated for more than 5 consecutive years. Proportion of retained foliar biomass was positively related to growth of Douglas-fir and grand fir in central Washington (Nichols 1988), implicating the negative effects of defoliation. In our study we were not able to demonstrate an effect of defoliation on height growth of subalpine fir or Engelmann spruce, even though they sustained more defoliation than Douglas-fir. Perhaps these species, being more shade-tolerant than Douglas-fir, were better able to recover following insect feeding, masking the effect of only 2 years of defoliation.

The amount of defoliation we observed was strongly influenced by tree stature; other variables were of lesser importance. Taller trees of all species incurred more defoliation than smaller trees (table 7). This was expected because budworm tend to feed near the tops of trees but drop down when foliage supplies become limiting. In light to moderate outbreaks such as we experienced in this study, foliage likely was not a limiting factor for the insect so they probably did not move downward very much. Furthermore, budworm larvae on small trees less than 3 feet tall are easy prey for birds and ants—at least half of the larvae on small trees may be removed (Carlson and others 1984). Because defoliation increased with increasing height for all species, potential crop trees—the taller ones with more live crown—may be more at risk than smaller trees. Douglas-fir trees with poor crown ratios, in plots with lots of variation in height, received the most defoliation. Subalpine fir trees with poor prerelease 10-year radial growth, on plots with low variation in height, were impacted most by budworm. The common thread between defoliation on Douglas-fir and subalpine fir appears to be some measure of tree vigor. Poor crown ratios indicate poor vigor for Douglas-fir, whereas poor prerelease growth rate seems to be the indicator for subalpine fir.

MANAGEMENT IMPLICATIONS

This study suggests that culturing advance regeneration on productive sites in the Northern Rocky Mountains may not be wise if the primary objective is to produce timber. Volume production may be mediocre compared to yields expected from seral, even-aged regeneration established following harvest. Furthermore, the increased susceptibility of advance regeneration to western spruce

budworm should not be taken lightly. Moderate to heavy defoliation in epidemics reduced expected yields more than 18 percent in Douglas-fir stands in British Columbia, Canada (Alfaro and others 1985). Repeated defoliation along with the mediocre height growth response in stands like we studied could result in yield reductions of more than 40 percent at rotation compared to yields from stands composed of seral species. These losses simply would not be acceptable on productive sites where growing timber is deemed important. In contrast, even-aged, seral conifer regeneration established subsequent to harvest will likely incur only light defoliation and little or no impact on height and diameter growth despite high budworm populations in susceptible adjacent stands (Carlson and others 1988).

But if the land manager decides that management of advance regeneration is his best option, after considering all important resource values, here are a few suggestions for enhancing timber values:

1. Select the most vigorous individuals as leave trees. These will be full crowned, deep green in color, with straight boles and rapid terminal leader growth. These trees will release quickest and grow fastest.

2. Remove all of the overstory stand as soon as possible, preferably in one cutting. Try to minimize logging damage to the residual understory because the shade-tolerant species are highly vulnerable to stem and root diseases if they are injured.

3. Provide the residual stand with room to grow. A thinning 3 to 4 years following overstory removal may be appropriate. Thinning will reduce susceptibility to western spruce budworm and will encourage rapid growth of residual trees.

4. Give preference to seral tree species. There will always be a few of these in the understory.

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APPENDIX: DERIVATION OF VALUES IN TABLE 8

CURRENT STUDY. Used regression models and for 11-year height and 12-year d.b.h. models. Pretreatment height growth, although not measured, was assumed to be similar to the posttreatment growth of the control stands.

JOHNSTONE (1978). Estimated height growth from curves in fig. 1 and fig. 2. Used curve for 4.0 ft average height, and 10 years after logging. Estimates are 8 ft at 10 years after logging and 4 ft at logging, so net is 4 ft, or 0.4 ft per year after harvest. We extrapolated curves 10 years prior to harvest and used the same technique. (Weak, but probably reasonably accurate). Johnstone had no diameter growth information for the advance regeneration.

SEIDEL (1980). Direct from table 1, line 1 (for all trees), for height and diameter. Preharvest diameter growth was assumed to be the same as the growth for 1975-76, the period just following harvest, because he did not cut down trees so he could measure preharvest growth.

FERGUSON AND ADAMS (1980). Height estimated from fig. 2, changing centimeters to feet.

McCAUGHEY AND SCHMIDT (1982). Height estimated from fig. 13. All four forests were similar, so we chose the Dixie, which may have a little slower growth than the others, but not significantly so.

HELMS AND STANDIFORD (1985). Used data from table 2, for the 20-30-cm release class. Assumed 25 cm as average postrelease growth, and converted to feet. Prerelease data taken directly from table. Postrelease diameter growth was obtained from page 9, item 2. We used growth for the intermediate prerelease diameter, and converted to feet. Except for reference to Standiford's MS thesis, this paper contains no information on prerelease diameter growth rate.

OLIVER (1986). Used figures in table 2. Used mean value of *Y* for the 0-8 year period, and divided by 8 to get annual diameter growth after harvest and thinning. No data for preharvest diameter growth. For preharvest height growth, we used table 1, and live crown pct of 70, where 3-year growth = 1.39. This value was converted to annual growth. For postharvest height growth, we used table 2, 0-8 year period, and divided by 8 to get annual mean growth of 0.29 ft. According to Oliver's data, for a given type of tree, height growth rate decreased following harvest and thinning.

Carlson, Clinton E.; Schmidt, Wyman C. 1989. Influence of overstory removal and western spruce budworm defoliation on growth of advance conifer regeneration in Montana. Res. Pap. INT-409. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 14 p.

Twelve-year postharvest diameter growth of advance Douglas-fir, Engelmann spruce, and subalpine fir regeneration and 11-year height growth of Douglas-fir and subalpine fir accelerated in response to decreasing competition. Competition was reflected in degree of overstory removal and change in plot basal area. Notwithstanding the influence of change in competition, the most influential variable affecting postharvest height and diameter growth was 10-year radial growth prior to overstory removal; trees growing well before harvest grew well after harvest. Postharvest mortality was greatest where about 50 percent of the overstory was removed. Defoliation by western spruce budworm reduced growth of Douglas-fir but did not affect subalpine fir or Engelmann spruce.

KEYWORDS: competition, stand density, insect impact, release

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Mule Deer Diets on a Chained and Seeded Central Utah Pinyon-Juniper Range

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RESEARCH SUMMARY

Diets of mule deer (*Odocoileus hemionus hemionus*) were studied on a central Utah chained and seeded pinyon (*Pinus edulis*) and Utah juniper (*Juniperus osteosperma*) site. Pellet groups were collected from swept plots at 4- to 12-week intervals between November 1985 and September 1986 and analyzed with the microhistological technique. A total of 24 forage items were identified, of which 13 occurred in greater than trace quantities (>1 percent relative composition). Woody species made up the bulk of all samples, 70 to 98 percent. Forb content ranged from 1 to 19 percent relative composition in all samples. Grasses made up 1 to 10 percent of all samples. Several seeded species—big sagebrush (*Artemisia tridentata*), alfalfa (*Medicago sativa*), and wheatgrasses (*Agropyron* spp.)—were seasonally important in deer diets.

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INTRODUCTION

Pinyon (*Pinus* spp.) and juniper (*Juniperus* spp.) habitats are a large proportion of winter-spring mule deer ranges in the Great Basin of the Western United States. Forage values have declined on much of this area as a result of overgrazing, fire suppression, and dominance by overstory species (Arnold and others 1964; Tausch and others 1981).

In the last 40 years, large areas of pinyon-juniper have been treated to increase forage production for deer or domestic livestock. At least 138,000 ha have been treated in Utah alone (J. Fairchild, personal communication). Treatment typically consists of removal of the tree canopy by mechanical means (chaining, cabling, or dozing), fire, or herbicides. Seeding is often necessary where desirable forage species are absent or too sparse to respond to treatment. Diverse mixtures are superior to monocultures in providing forage for mule deer (Plummer and others 1968). Such mixtures usually contain a variety of native and introduced grasses, forbs, and shrubs.

Despite the number of treatment projects, studies of mule deer food habits in the pinyon-juniper type have largely been restricted to unmodified habitats (Boeker and others 1972; Hansen and Dearden 1975; Ritchens 1967). Published information from modified pinyon-juniper habitats is limited. McCullock (1969) collected food habit data from a seeded burn in northern Arizona. Terrel and Spillet (1975) presented results from a chained and seeded site in central Utah.

Results of these studies showed considerable variation with season, location, year, and sampling technique. In the presence of such variability, site-specific information is important for management purposes.

This study was undertaken to characterize forage used by mule deer on a chained and seeded central Utah winter-spring range. Fecal samples were collected over 11 months and analyzed with microhistological procedures.

STUDY AREA

We conducted this study at the Manti Face pinyon-juniper chaining in Sanpete County, central Utah. The treated area encompasses 242 ha at elevations of 1,820 to 1,983 m. Soils are limestone-derived Fontreen Series cobbly loams (USDA SCS 1981). Long-term average annual precipitation is 33 cm.

Prior to treatment, the site was dominated by a closed stand of mature pinyon-juniper with depleted understory vegetation. In November 1961, the site was double-chained and aerial seeded. Between chainings, a seed mixture of native and introduced grasses, forbs, and shrubs was applied by fixed-wing aircraft (table 1).

Because the site is managed primarily for wild ungulates, grazing by domestic livestock has been limited. It was rested for 12 years to enhance establishment of seeded species and recovery of native vegetation. Since then, the site has received five seasons of cattle use and three seasons of sheep use in late spring (May and June) at stocking rates of 1 to 5 ha per animal unit month (AUM).

Posttreatment vegetation in 1986 was dominated by perennial grasses, including fairway (crested) wheatgrass (*Agropyron cristatum*), intermediate wheatgrass (*A. intermedium*), western wheatgrass (*A. smithii*), bluebunch wheatgrass (*A. spicatum*), pubescent wheatgrass (*A. trichophorum*), smooth brome (*Bromus inermis*), Russian wildrye (*Psathyrostachys juncus*), Indian ricegrass (*Oryzopsis hymenoides*), and bulbous bluegrass (*Poa bulbosa*). Alfalfa (*Medicago sativa*) was the most abundant forb. The most abundant shrub species were big sagebrush (*Artemisia tridentata*), black sagebrush (*A. nova*), rubber rabbitbrush (*Chrysothamnus nauseosus*), low rabbitbrush (*C. viscidiflorus*), and antelope bitterbrush (*Purshia tridentata*). Reinvasion by

Table 1—Seed mixture and bulk rate applied on Manti Face pinyon-juniper study site, Utah

Species	Rate
	Kg/ha
Fairway (crested) wheatgrass (*Agropyron cristatum*)	3.5
Intermediate wheatgrass (*A. intermedium*)	1.8
Pubescent wheatgrass (*A. trichophorum*)	1.8
Smooth brome (*Bromus inermis*)	0.9
Russian wildrye (*Psathyrostachys juncus*)	0.9
Alfalfa (*Medicago sativa*)	0.9
Yellow sweetclover (*Melilotus officinalis*)	0.4
Big sagebrush (*Artemisia tridentata*)	0.4
Rubber rabbitbrush (*Chrysothamnus nauseosus*)	0.4
Total	11.0

pinyon and juniper has been minimal. Tree density was approximately 60 stems per ha, the majority of which were junipers in the sapling age class (0.5 to 6.0 cm basal diameter). The site is typical of many foothill pinyon-juniper treatment projects in central Utah.

DATA COLLECTION AND ANALYSIS

Ten 3-m circular plots were randomly located on the site in 1985. Plots were swept clean of all mule deer fecal materials. The plots were sampled six times between November 1985 and September 1986, at 4- to 12-week intervals. All pellet groups were removed at each sampling.

We analyzed samples following the microhistological procedures outlined by Sparks and Malechek (1968). Pellet groups were milled and thoroughly homogenized. Ten slides were prepared from each sample. We read 200 microscope fields per sample, 20 from each slide. Holechek and Vavra (1981) recommended a sample size of nine slides of 20 fields each to estimate all major diet items (>20 percent relative composition) within 10 percent of the mean at a 95 percent confidence level. All plant fragments within a field were identified and counted. Fecal composition was expressed as mean relative fragment density for each identified forage item. Composite reference samples of the most abundant grass, forb, and browse species (collected from the study area) were similarly prepared to aid in plant identification.

RESULTS AND DISCUSSION

We collected 59 pellet groups during the sampling period. Sample size per collection ranged from five groups (November 1985) to 16 groups (April 1986). Pellet groups were deposited through the month of June and again in September, indicating that deer use of this site extends beyond early spring.

We identified 24 forage items: six grasses, six forbs, and 12 shrubs and trees. Some items were identified only to genus, as multiple species present on the site were indistinguishable by microhistological techniques. Of these 24 items, 13 occurred in greater than trace (1 percent) amounts (table 2). However, in all samples, the bulk comprised three to four forage taxa. Boeker and others (1972) observed similar feeding patterns on an untreated pinyon-juniper site in New Mexico. Winter diet composition and relative proportions were similar to results from a nearby pinyon-juniper site reported by Terrel and Spillet (1975).

Woody plants were the largest component in all samples, representing 70 to 98 percent of the total composition (fig. 1). The relative composition of browse changed little over the sampling period. Browse content was lowest in the April samples and highest in November. These results were similar to those reported by Boeker and others (1972).

Twelve browse plants were present in greater than trace (1 percent) amounts (table 2). Of these, Utah juniper (*Juniperus osteosperma*) and big sagebrush occurred in the greatest quantity. The proportion of juniper was higher than reported in previous studies (Terrel and Spillet 1975). Juniper is generally considered an emergency food of low preferences and digestibility (Ritchens 1967; Smith and Hubbard 1954). Increased juniper consumption has been associated with persistent low temperatures and snow conditions limiting access to other forages (Hansen and Dearden 1975; Leach 1957). Weather data were not collected in this study, so the

Table 2—Mean relative composition of forage plants occurring in greater than trace amounts (1 percent) in mule deer fecal samples collected November 1985 to September 1986 on Manti Face pinyon-juniper treatment study site, Utah, as determined by microhistological analysis

Species	Date of collection					
	Nov. 1985	Feb. 1986	Mar. 1986	Apr. 1986	June 1986	Sept. 1986
Grasses						
Agropyron spp.	—	3.6	2.9	3.6	3.6	3.7
Bromus spp.	—	—	2.2	—	—	—
Poa spp.	—	1.7	4.0	5.6	2.0	—
Forbs						
Medicago sativa	—	1.3	2.6	18.8	5.5	5.2
Browse						
Artemisia tridentata	2.0	15.7	24.7	48.4	15.3	5.0
Atriplex canescens	6.2	—	—	—	—	—
Berberis repens	17.7	3.6	—	—	—	3.0
Cercocarpus spp.	17.7	3.6	—	—	30.2	1.2
Ephedra spp.	—	4.7	—	—	—	1.1
Juniperus osteosperma	63.4	58.3	59.2	21.2	32.5	71.7
Pinus edulis	—	2.4	—	—	—	1.9
Purshia tridentata	—	2.1	—	—	—	—
Quercus gambelii	5.8	—	—	—	9.1	6.5

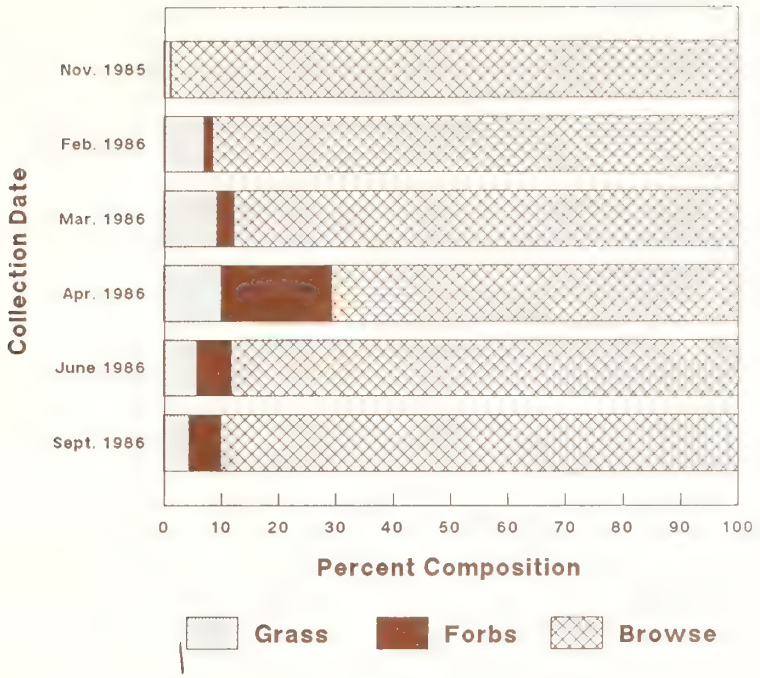

Figure 1—Relative composition of deer fecal samples collected November 1985 through September 1986 at Manti Face pinyon-juniper chaining, Utah, as determined by microhistological analysis.

impact of these factors cannot be assessed. However, persistent deep snow cover was generally lacking during the winter of 1985 to 1986. Presumably, deer had access to other forages during most of the sampling period. The high proportion of juniper could reflect bias in the fecal analysis procedure. Several investigators have reported overestimation of woody browse species due to differential digestibility of plant fragments (Anthony and Smith 1974; Hansen and others 1973).

Forbs were present in all samples, representing 1 to 19 percent of the total summer samples. This pattern has also been reported in deer diets on other pinyon-juniper sites (Anderson and others 1965; Boeker and others 1972).

The forb component was almost entirely alfalfa, while other species were present only in trace amounts (< 1 percent). Actual alfalfa content was possibly much greater than indicated by results of the fecal analysis because of its high digestibility. Alexander (1980) reported that highly digestible forbs taken by tame deer were not detected in fecal samples. Other studies have indicated that microhistological procedures can underestimate forb content (Anthony and Smith 1974; Free and others 1970; Gill and others 1983).

Mule deer consume alfalfa from agricultural plantings, according to Kufeld and others (1973), Leach (1957), and Martinka (1968). However, use of alfalfa on seeded pinyon-juniper ranges has not been previously documented. Results of this study indicate that alfalfa is an important forage in deer diets, particularly in early spring.

Grasses were present in all samples, with relative composition of 1 to 10 percent (fig. 1). Grass content was highest in the March and April samples. Three genera were present in greater than trace amounts (table 2). Of these, wheatgrasses and bluegrasses were most abundant. The five wheatgrass species present on the site could not be distinguished from one another with microhistological procedures; therefore their relative importance to mule deer could not be assessed.

The observed proportion of grasses in deer diets was higher than reported in studies from untreated pinyon-juniper habitats (Anderson and others 1965; Boeker and others 1972), though lower than amounts reported on other treated ranges (McCullock 1969; Terrel and Spillet 1975). The higher relative proportion of grass in the diet (in comparison to studies in untreated pinyon-juniper habitats) could reflect greater grass availability. Terrel and Spillet (1975) reported significantly higher consumption of grasses on a chained and seeded site where grasses were more abundant, than on an immediately adjacent untreated area.

CONCLUSIONS

Of the species seeded on this site, big sagebrush, alfalfa, and wheatgrasses occurred most frequently in deer fecal samples. Because of the importance of big sagebrush, future seedings in the pinyon-juniper type should include sagebrush accessions preferred by mule deer, such as those described by Welch and others (1981, 1983). Given the palatability of alfalfa to domestic livestock, spring grazing on these sites should be limited or delayed when production of deer forage is a management priority.

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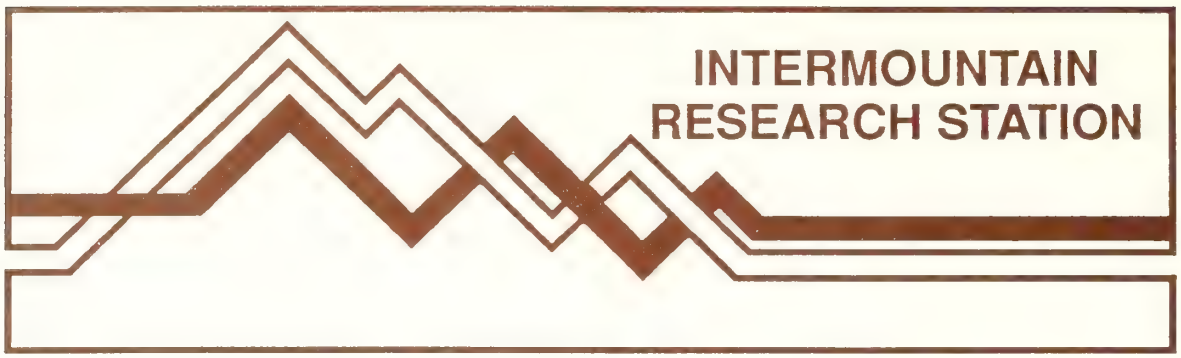
Study of the seasonal use by mule deer of some native and introduced species on a pinyon-juniper restoration project showed that woody species made up the bulk of pellet samples, followed by forbs and grasses. Land managers are advised on seeding and grazing practices for enhancing big game habitats.

KEYWORDS: *Odocoileus hemionus hemionus,* food habits, *Pinus edulis*, *Juniperus osteosperma*, *Medicago sativa*, *Artemisia tridentata*, *Agropyron* spp., microhistological studies, Great Basin, Western United States



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Ignition Probabilities of Wildland Fuels Based on Simulated Lightning Discharges

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RESEARCH SUMMARY

Fine fuel samples from Northwestern forest areas were subjected to an electric arc discharge that simulated the lightning continuing current. The important fuel state parameters and the ignition probabilities were determined using logistic regression.

The ignition probabilities for duff from short-needled conifer species were found to depend almost entirely on the depth of the fuel bed. In the case of litter and duff from long-needled species, ignition probabilities depend mostly on the ovendry fuel moisture.

Ignition probabilities also depend on the duration of the arc only, with current flow and diameter having no detectable effect. Because the continuing current durations can be fit well by a Weibull distribution for both positive and negative discharges to ground, the probabilities conditional on the current duration can be converted to marginal probabilities per discharge. The necessary integrations were done and the results are presented.

Marginal ignition probabilities are given in four forms. Tables give the probabilities for selected values of the independent variables. Graphs of the probabilities are also shown. Equations based on curve fits to the tabulated values accompany the graphs. Finally, a FORTRAN program that uses a rapid integration scheme to give the probabilities is included in subroutine form. All these products are valid only over the range of values for the independent variables as specified in the paper.

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INTRODUCTION

Land management agencies are now using lightning location equipment in fire management operations. Some implications of this technology were set forth by Latham (1979), including the steps necessary to accomplish the location and timing of lightning-caused fires. One of these steps is assessing the probability that lightning discharge to ground will ignite fuels.

A previous investigation of ignition probability (Fuquay and others 1979) used an energy argument in which the available energy density in the lightning continuing current was compared to the fuel's heat of ignition as used in fire models. The authors concluded that further investigation was needed to improve the accuracy of the ignition probability algorithm.

The details of that further investigation are contained in a series of papers. The first paper (Latham 1987) describes the equipment needed to do the testing. The second (Latham 1989) reports the details of the electric arc as an energy source as it was used in the experiments. The third and present publication describes the ignition experiments and the results. This publication also formats the results for application and discusses probability of ignition for lightning continuing currents. The report provides tables, curves, formulas, and algorithms for implementation of the ignition probabilities together with suggestions for use.

DATA AND ANALYSIS

The electric arc source was used to penetrate 1,666 fuel beds with a dc arc discharge. The current and duration of the discharge were varied, as were the fuel bed composition, depth, packing ratio, and moisture. For each fuel bed, the result of ignition or no ignition was recorded. The fuel types used in the analysis were ponderosa pine litter, punky wood (both in chunks and fine powder), peat moss (commercial samples), Douglas-fir duff, lodgepole pine duff, and high-altitude mixed species (primarily Engelmann spruce) duff.

The dependent variable has only two values (1 = ignition or 0 = no ignition), so a logistic regression model was used to estimate the probability of ignition. The logistic model gives a number between 0 and 1, which is appropriate since we are estimating a probability. The maximum likelihood estimates for model parameters were obtained from the SAS procedure CATMOD. The models were constructed from the original observations rather than by grouping the data.

One step in the investigation was determining which independent variables to include in the models. The statistic used for these tests was minus twice the maximized log likelihood (Efron 1978). When candidate variables are added one at a time, the difference in log likelihoods has a chi-square distribution with 1 degree of freedom.

After the models were estimated, a chi-square type statistic, *Cg*, was used to evaluate how well the models fit (Lemeshow and Hosmer 1982). The statistic is calculated from a table of observed and expected values and has a distribution closely approximated by a chi-square distribution with 8 degrees of freedom. Test results by fuel type are shown in table 1. A *p*-value greater than 0.10 indicates that the model fits the data well.

Two important results were apparent from the analyses. The primary result was that the most important of the variables associated with the discharge was its duration. We checked this carefully, because of our original conjecture that the energy density would be important.

Table 1—Evaluation of the fit of logistic regression equations to the ignition data. *Cg* and *p*-value are explained in the text

Fuel	Sample size	*Cg*	*p*-value
Ponderosa pine litter	722	8.61	0.38
Punky wood (rotten, chunky)	136	4.01	.86
Punky wood powder (4.8 cm deep)	105	4.43	.82
Punky wood powder (2.4 cm deep)	70	2.75	.95
Lodgepole pine (duff)	90	6.81	.56
Douglas-fir (duff)	117	1.62	.99
Engelmann spruce (duff)	160	11.86	.16
Peat moss (commercial)	266	3.11	.93

The fact that the duration alone can characterize the discharge for ignition is very significant. It is the one variable associated with the continuing current discharge that is relatively easy to measure in the field (as opposed to the current or the diameter). Second, we found that the moisture content (for moistures less than 40 percent) plays a very small role in the ignition of duff from short-needled species; the depth of the bed is more influential.

LOGISTIC REGRESSION COEFFICIENTS

We broke the coefficients of the exponential in the logistic regression for each fuel type into two parts for convenience in later processing. One coefficient (B) multiplies the duration of the arc discharge, and the other (A) contains the coefficients and variables that are specific to the fuel, such as fuel moisture, bed depth, bulk density, and so on. These coefficients are used to determine the probability of ignition using the equation:

$$\mathrm{pci}(A,B,t) = 1/(1 + \exp(-A - Bt)) \qquad (1)$$

where the experimentally determined coefficients are given in table 2. These values are used with equation (1) to generate conditional ignition probabilities when the duration of a continuing current event and fuel parameters are known.

Present lightning location systems do not measure the duration of the continuing current. In fact, they do not even identify those lightning discharges that have a continuing current component. This situation can be partly corrected. We do have a number of measurements, at least for northwestern storms, for the duration of continuing currents from both negative and positive discharges to ground. These measurements can be combined with the conditional probabilities to give a probability per lightning event.

MARGINAL IGNITION PROBABILITY

What we want to know is the probability of an ignition, given the occurrence of an electrical discharge in the fuel, that is, the marginal probability of ignition with respect to discharge duration. We can now estimate conditional ignition probability, given the duration of the discharge and the fuel state, from equation (1) and table 2. If we know the probability distribution for continuing current duration, we can find the marginal probability of ignition by multiplying the two probabilities and adding them up over all durations.

We have determined that the continuing current probability is best fit by the Weibull (see appendix A) distribution (Kappenman 1988):

$$\mathrm{p}(t,n,s) = \left(\frac{n}{s}\right)\left(\frac{t}{s}\right)^{n-1} \exp\left[-\left(t/s\right)^{n}\right] \qquad (2)$$

where t is the duration (msec) and the values of n and s are 1.6 and 207.8 for negative discharges, and 2.3 and 69.3 for positive discharges.

The adding-up is done by the integral:

$$\mathrm{pi}(n,s,A,B) = \int_0^{\infty} \mathrm{p}(t,n,s)\ \mathrm{pci}(A,B,t)dt \qquad (3)$$

that must be solved by a numerical integration. We performed the integrations necessary and obtained marginal probability distributions as given in table 3 and appendix B. The simple equations of table 3 result from a "best fit" approach starting with simple functions.

We have also developed a FORTRAN algorithm (appendix C) for the marginal probability. This algorithm performs the integration necessary to obtain the marginal distribution as presented above. The integration is a 6-point Gaussian quadrature using Laguerre polynomials. The results check within 2 to 3 percent of the Romberg quadrature used to calculate the values of appendix B. This precision, considering the other uncertainties in application of the algorithms, is entirely adequate.

Table 2—Coefficients for the probability distributions of Equation (2). *Mf* is the fuel moisture in percentage of dry weight, δ is the duff depth in cm, and ρb is the bulk density in g/cm^3

Fuel	A	B
Ponderosa pine litter	$0.97 - 0.19Mf$	0.012
Punky wood (rotten, chunky)	$-0.59 - 0.15Mf$	.005
Punky wood powder (4.8 cm deep)	$1.2 - 0.12Mf$	.002
Punky wood powder (2.4 cm deep)	$0.13 - 0.05Mf$	.005
Lodgepole pine (duff)	$-5.6 + 0.68\delta$	.007
Douglas-fir (duff)	$-7.1 + 1.4\delta$	.006
Engelmann spruce (duff)	$0.79 - 0.081Mf - 8.5\rho b$	.011
Peat moss (commercial)	$0.42 - 0.12Mf$	.005

Table 3—Equations approximating the curves of figs. 3 through 10. *Mf* is the fuel moisture in percentage of dry weight and δ is the bed depth in cm. These equations are valid only within the specified ranges

Fuel	pineg	pipos
Ponderosa pine litter	$1.04 \exp(-0.054Mf)$	$0.92 \exp(-0.087Mf)$
Punky wood (rotten, chunky)	$0.59 \exp(-0.094Mf)$	$0.44 \exp(-0.11Mf)$
Punky wood powder (4.8 cm deep)	$0.9 \exp(-0.056Mf)$	$0.86 \exp(-0.06Mf)$
Punky wood powder (2.4 cm deep)	$0.73 - 0.011Mf$	$0.6 - 0.11Mf$
Lodgepole pine (duff)	$(1+\exp(3.84-0.6\delta))^{-1}$	$(1+\exp(5.13-0.68\delta))^{-1}$
Douglas–fir (duff)	$(1+\exp(5.48-1.28\delta))^{-1}$	$(1+\exp(6.69-1.39\delta))^{-1}$
Engelmann spruce (duff)	$0.8 - 0.014Mf$	$0.62 \exp(-0.05Mf)$
Peat moss (commercial)	$0.84\exp(-0.06Mf)$	$0.71 \exp(-0.07Mf)$

Note: Range of validity is 0 to 40 percent for *Mf* and 0 to 10 cm for δ. Do not use outside this range.

SUGGESTIONS FOR USE

Ignition probabilities have a wide range of uses, from preseason planning to dispatch of fire suppression forces. Specific applications are: daily fire-danger rating, preattack (short-range) planning, prepositioning of fire-fighting forces, and dispatch of fire-spotting flights. These uses of ignition probability depend on the available knowledge about the variables involved in the calculations. Generally, the farther from real-time the application is, the poorer the knowledge about the fuel variables.

For all applications that are not real-time, the marginal probability distributions should be used with area lightning statistics. If the duration of discharge is not known, but the type of discharge is (as in a real-time application using lightning location systems), the marginal probabilities given in appendixes B and C should be applied. The simple formulas in table 3 may be used for this purpose as well.

When applying tabulated, graphed, or simple formula approximations, the probabilities given are per continuing current. Almost all positive discharges have a continuing current. The probabilities for positive discharges thus do not need to be corrected, and may be used as is per positive event. Negative discharges to ground do not all have continuing currents. In fact, only about one in five do. When using the probabilities pneg, then, a correction must be applied; that is, a multiplier of 0.2. The FORTRAN program of appendix C has this correction built in, so if the program is checked against the tables (as it should be when implemented), the negative probabilities will seem to be too small.

Application of the distributions to species other than those that we studied is possible according to the suggestions of table 4. These are based on Agriculture Handbook 519 (Little 1978) and consultation with Dr. J. K. Brown of the Intermountain Fire Sciences Laboratory. In addition, we feel that short grasses will behave much the same as the loose, low-organic-content peat moss that we used in the experiments, and tall grasses, such as sawgrass, will behave as ponderosa pine litter, because the ignition will take place in the clumps of dead grass rather than in the standing dead spears. If species are not mentioned in table 4, we suggest that consideration of cover type be the guide.

Because of species/cover type dependence, the primary use of probabilities will eventually be in a geographic information system (GIS). In such use, a calculation for each discharge may not be necessary. Marginal ignition probabilities can be calculated in advance of storms. To do this, of course, one needs the relative number of positive and negative strikes. (About one positive for about every 50 negatives.) Indeed, for several species, the ignition probability is nearly static, because these depend primarily on duff depth. The ignition probabilities can be displayed, perhaps in color, and the discharges superimposed on them. The resulting display would be projected ignitions, not surviving fires. In order to determine survivability, rain and projected fire growth models should be connected to ignitions. A learning program operating in the GIS should be possible to improve the usefulness of the ignition probabilities and survival potential. More specific application of ignition probabilities depends on identification of continuing currents and measurement of their duration in lightning locating systems.

Table 4—Application of fuels studied to other species

Studied fuels				
Ponderosa pine	**Lodgepole pine**	**Douglas-fir**	**Engelmann spruce**	**Peat (commercial)**
Longleaf pine	Eastern white pine	Bald cypress	Spruce-fir	All grasses
Slash pine	Limber pine	All spruce (except Engelmann)	All hemlock	Eastern tamarack (peat)
Loblolly pine	Tamarack	Giant sequoia	Subalpine fir	Black spruce (peat)
Pond pine	Jack pine	Eastern hemlock	Pacific silver fir	Other peat
Pitch pine	Virginia pine	All cedars and juniper	Grand fir	All mosses
Shortleaf pine	Sand pine		Noble fir	
Red pine	Spruce pine		California red fir	
Monterey pine	Pinyons			
Sugar pine	White fir			
Jeffrey pine	Redwood			
Digger pine	Western white pine			
Knobcone pine	Bristlecone pine			

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APPENDIX A: WEIBULL DISTRIBUTIONS FOR LIGHTNING CURRENTS

Continuing current duration distributions are well fit by the Weibull distribution:

$$p(t,n,s) := \left[\frac{n}{s}\right] \cdot \left[\frac{t}{s}\right]^{n-1} \cdot e^{-\left[\frac{t}{s}\right]^{n}} \qquad (1)$$

where t is time, n is the shape parameter, and s the scale parameter.

The Weibull distribution is the statistic of choice for systems in which failure of the whole is contingent on failure of a part or parts of the whole. The probability of failure of the whole increases with time according to the value of n. Previously, the distribution of continuing currents was fit by a lognormal distribution. We found the Weibull to be a more satisfactory fit.

The distributions for negative and positive lightning strokes to ground (based on data from 141 negative strokes and 54 positive strokes) are found from equation (1) with the values:

$$\text{pneg} := p\left[\tau, 1.6, 207.8\right] \qquad \text{ppos} := p\left[\tau, 2.3, 69.3\right] \qquad (2)$$

where τ is duration in msec, pneg is the probability of occurrence of a negative continuing current of duration τ, and ppos is the probability of occurrence of a positive continuing current of duration τ. The results of this exercise are given in table 5 and figures 1 and 2.

Table 5—Values of the Weibull distribution for continuing currents. Pneg for negative discharges to ground, and ppos for positive discharges to ground. τ is the continuing current duration in msec

	Weibull distributions	
τ	pneg(X1000)	ppos(X100)
0	0	0
10	1.237	0.265
20	1.846	.623
30	2.304	.966
40	2.667	1.225
50	2.957	1.354
60	3.186	1.342
70	3.363	1.208
80	3.495	.995
90	3.586	.752
100	3.640	.523
110	3.662	.335
120	3.656	.198
130	3.624	.107
140	3.570	.054
150	3.497	.025
160	3.408	.010
170	3.305	.004
180	3.191	.001
190	3.068	
200	2.938	
210	2.802	
220	2.664	
230	2.524	
240	2.383	
250	2.243	
260	2.105	
270	1.970	
280	1.838	
290	1.710	
300	1.587	
310	1.469	
320	1.357	
330	1.249	
340	1.148	
350	1.052	
360	.963	
370	.878	
380	.800	
390	.727	
400	.659	
410	.596	
420	.538	
430	.485	
440	.436	
450	.391	
460	.351	
470	.314	
480	.280	
490	.249	

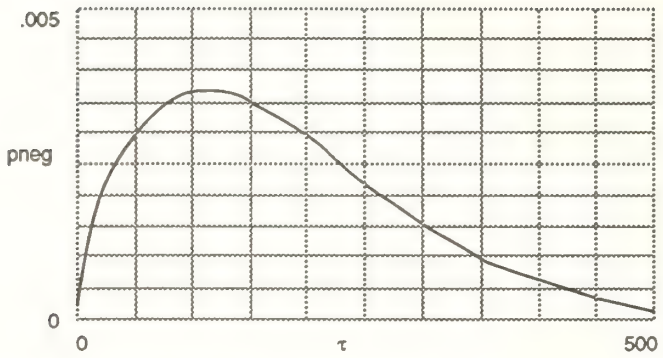


Figure 1—A plot of the Weibull probability distribution (pneg) for negative discharges to ground. is the duration in msec.

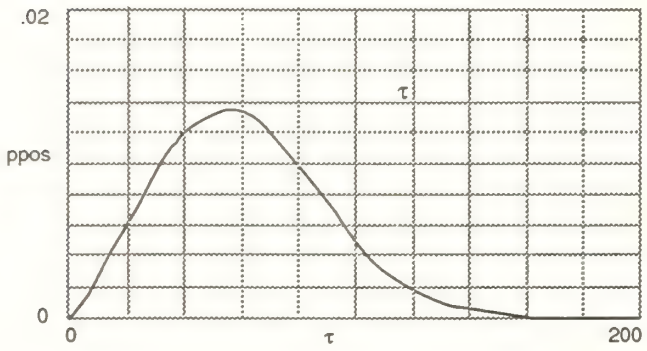
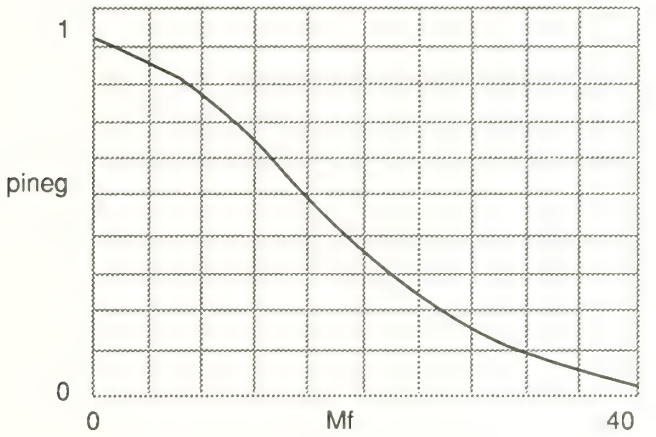


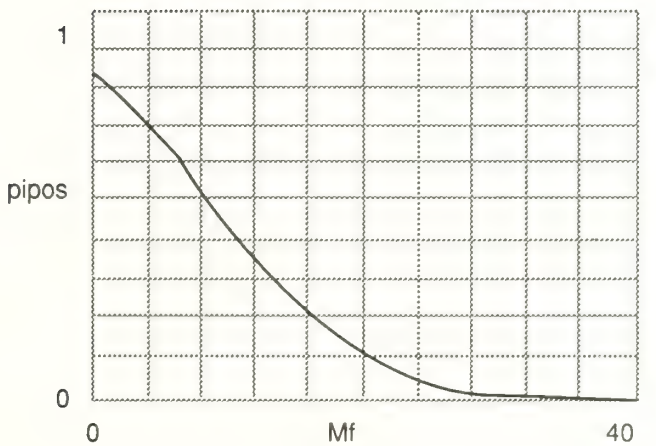
Figure 2—A plot of the Weibull distribution (ppos) for positive discharges to ground. τ is the duration in msec.

APPENDIX B: GRAPHS, TABLES, AND SIMPLE EQUATIONS FOR MARGINAL IGNITION PROBABILITIES



Mf	pineg
0	0.925
4	0.864
8	0.77
12	0.646
16	0.507
20	0.372
24	0.256
28	0.166
32	0.102
36	0.059
40	0.032

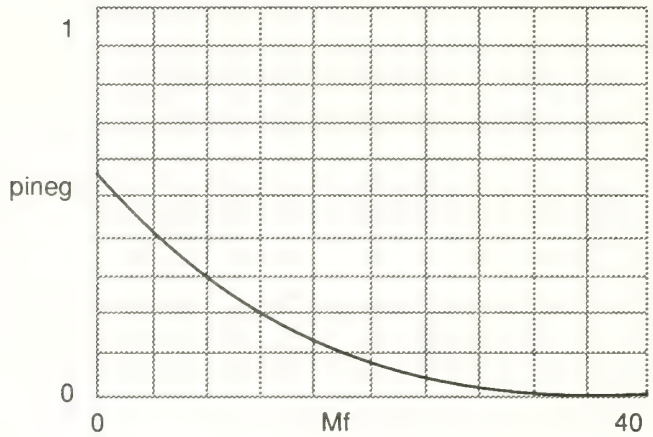
$$pineg = 1.04\ exp(-0.054Mf)$$



Mf	pipos
0	0.842
4	0.716
8	0.545
12	0.364
16	0.214
20	0.114
24	0.057
28	0.028
32	0.013
36	0.006
40	0.003

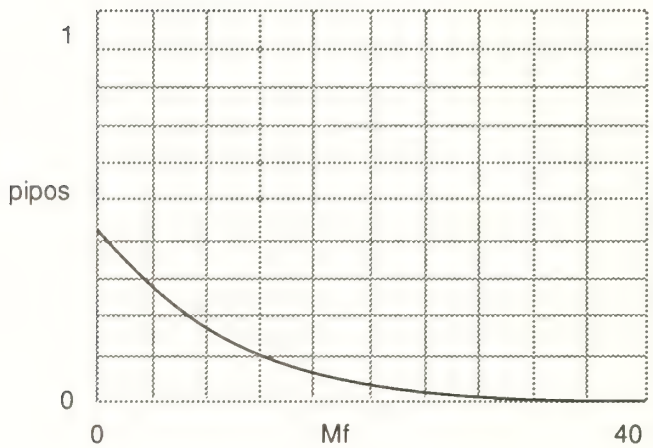
$$pipos = 0.92\ exp(-0.087Mf)$$

Figure 3—Marginal ignition probabilities for ponderosa pine litter. Pineg is the probability of ignition for negative discharges, pipos for positive discharges. Tabular values and simplified equations are given for convenience.



Mf	pineg
0	0.571
4	0.433
8	0.305
12	0.201
16	0.125
20	0.074
24	0.043
28	0.024
32	0.014
36	0.007
40	0.004

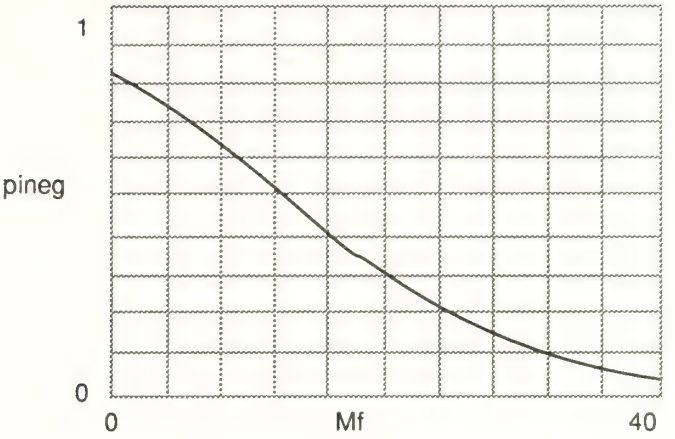
$$pineg = 0.595\ \exp(-0.094Mf)$$



Mf	pipos
0	0.43
4	0.293
8	0.186
12	0.112
16	0.065
20	0.037
24	0.02
28	0.011
32	0.006
36	0.003
40	0.002

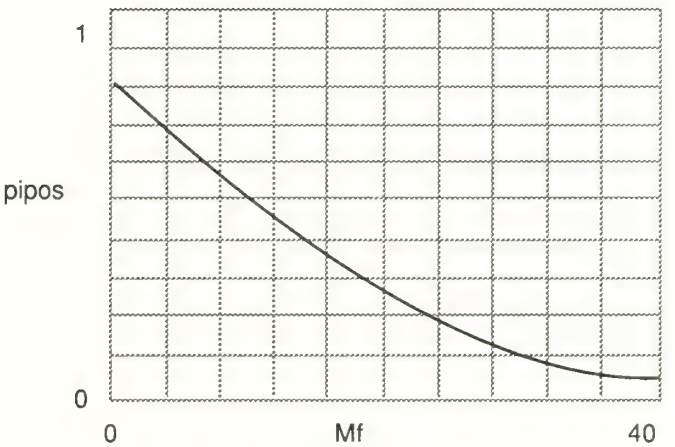
$$pipos = 0.439\ \exp(-0.114Mf)$$

Figure 4—Marginal ignition probabilities for rotten, chunky punky wood. Pineg is the probability of ignition for negative discharges, pipos for positive discharges. Tabular values and simplified equations are given for convenience.



Mf	pineg
0	0.821
4	0.742
8	0.643
12	0.529
16	0.412
20	0.304
24	0.214
28	0.144
32	0.095
36	0.061
40	0.039

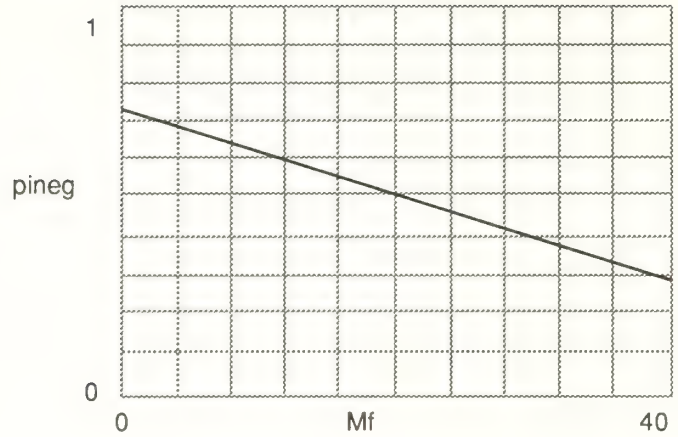
$$pineg = 0.9\ exp(-0.056Mf)$$



Mf	pipos
0	0.79
4	0.699
8	0.59
12	0.471
16	0.355
20	0.254
24	0.174
28	0.116
32	0.075
36	0.048
40	0.03

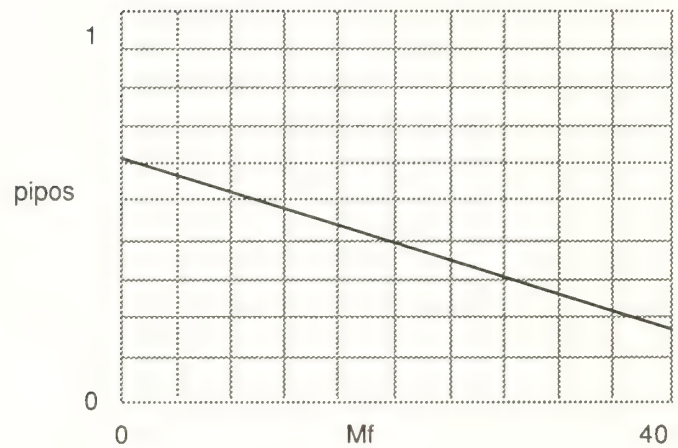
$$pipos = 0.86\ exp(-0.061Mf)$$

Figure 5—Marginal ignition probabilities for powdered punky wood, depth 4.8 cm. Pineg is the probability of ignition for negative discharges, pipos for positive discharges. Tabular values and simplified equations are given for convenience.



Mf	pineg
0	0.723
4	0.684
8	0.642
12	0.598
16	0.553
20	0.507
24	0.461
28	0.415
32	0.371
36	0.329
40	0.29

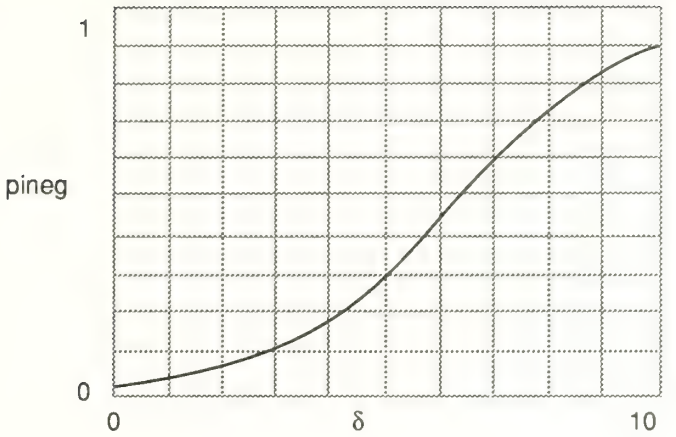
$$pineg = 0.73 - 0.011Mf$$



Mf	pipos
0	0.607
4	0.559
8	0.509
12	0.46
16	0.411
20	0.364
24	0.319
28	0.277
32	0.239
36	0.205
40	0.174

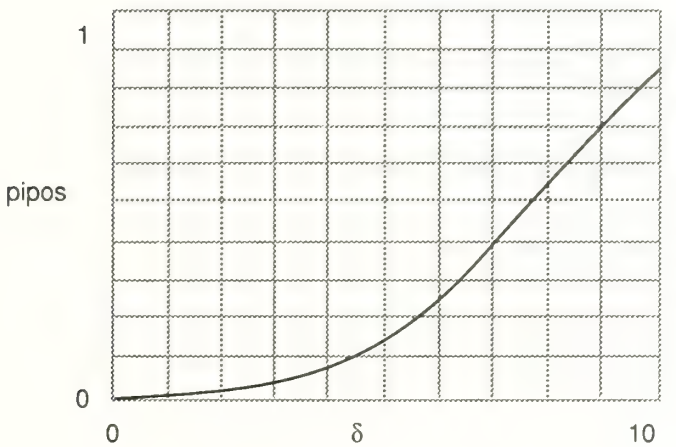
$$pipos = 0.6 - 0.11Mf$$

Figure 6—Marginal ignition probabilities for powdered punky wood, 2.4 cm deep. Pineg is the probability of ignition for negative discharges, pipos for positive discharges. Tabular values and simplified equations are given for convenience.



δ	pineg
0	0.019
1	0.036
2	0.066
3	0.117
4	0.195
5	0.305
6	0.442
7	0.59
8	0.725
9	0.83
10	0.902

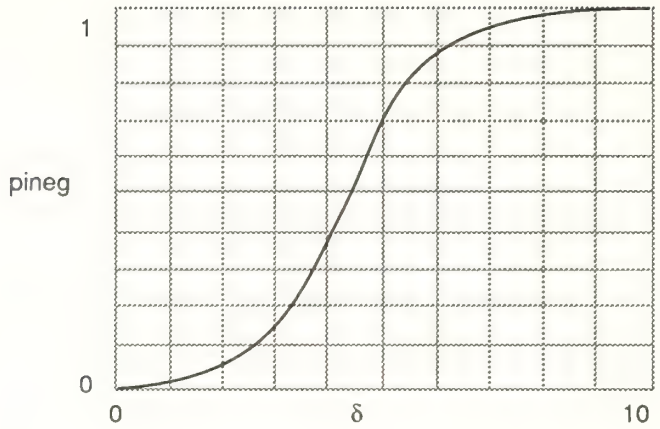
$$pineg = 1/(1 + \exp(3.84 - 0.6\delta))$$



δ	pipos
0	0.006
1	0.011
2	0.022
3	0.043
4	0.081
5	0.147
6	0.253
7	0.4
8	0.566
9	0.72
10	0.835

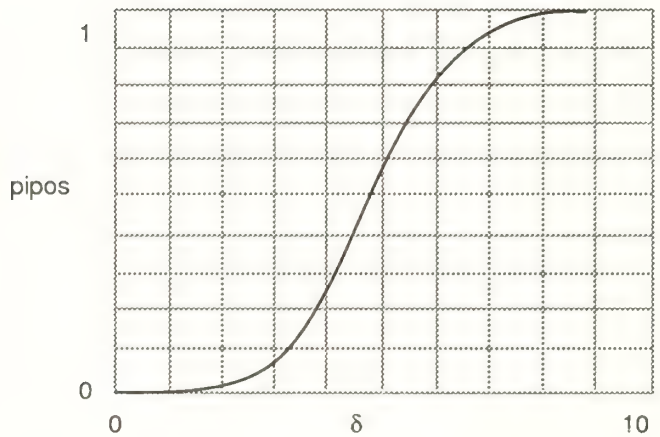
$$pipos = 1/(1 + \exp(5.13 - 0.68\delta))$$

Figure 7—Marginal ignition probabilities for lodgepole pine duff. Pineg is the probability of ignition for negative discharges, pipos for positive discharges. Tabular values and simplified equations are given for convenience.



δ	pineg
0	0.003
1	0.013
2	0.049
3	0.162
4	0.406
5	0.709
6	0.9
7	0.969
8	0.989
9	0.994
10	0.995

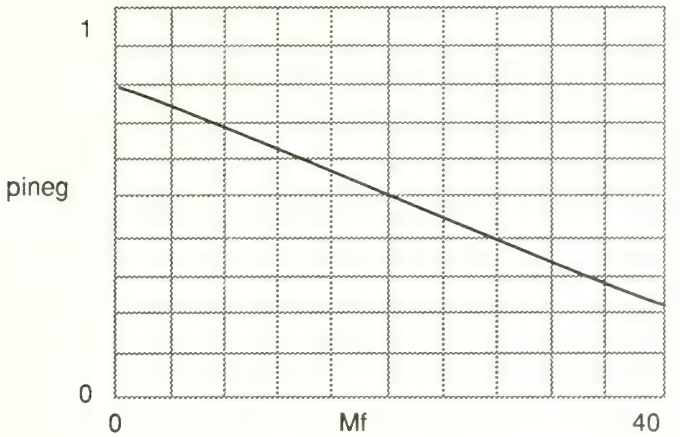
$$pineg = 1/(1 + \exp(5.49 - 1.28\delta))$$



δ	pipos
0	0.001
1	0.005
2	0.02
3	0.075
4	0.245
5	0.566
6	0.84
7	0.955
8	0.989
9	0.997
10	0.999

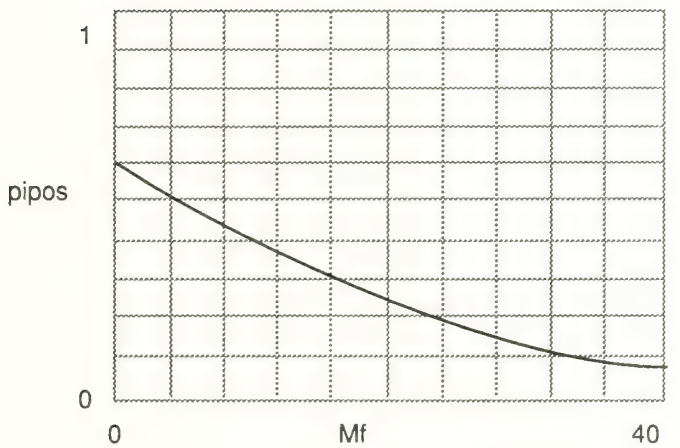
$$pipos = 1/(1 + \exp(6.69 - 1.39\delta))$$

Figure 8—Marginal ignition probabilities for Douglas-fir duff. Pineg is the probability of ignition for negative discharges, pipos for positive discharges. Tabular values and simplified equations are given for convenience.



Mf	pineg
0	0.79
4	0.741
8	0.687
12	0.628
16	0.567
20	0.505
24	0.444
28	0.386
32	0.33
36	0.279
40	0.233

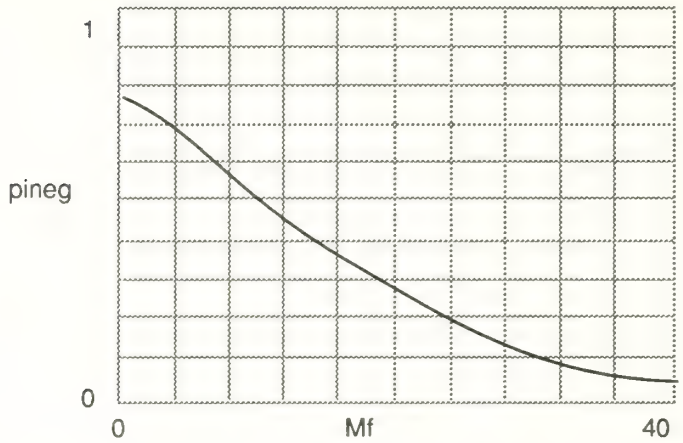
$$pineg = 0.8 - 0.014Mf$$



Mf	pipos
0	0.593
4	0.515
8	0.436
12	0.361
16	0.291
20	0.23
24	0.179
28	0.136
32	0.103
36	0.077
40	0.057

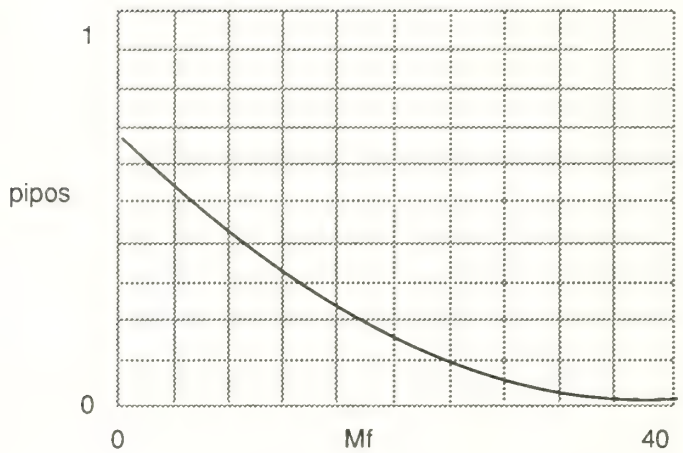
$$pipos = 0.62\ \exp(-0.051Mf)$$

Figure 9—Marginal ignition probabilities for high-altitude mixed species, primarily Englemann spruce. Pineg is the probability of ignition for negative discharges, pipos for positive discharges. Tabular values and simplified equations are given for convenience.



Mf	pineg
0	0.774
4	0.686
8	0.583
12	0.472
16	0.365
20	0.269
24	0.19
28	0.13
32	0.086
36	0.056
40	0.036

$$pineg = 0.839 \exp(-0.058Mf)$$



Mf	pipos
0	0.674
4	0.561
8	0.442
12	0.33
16	0.234
20	0.159
24	0.105
28	0.068
32	0.043
36	0.027
40	0.017

$$pipos = 0.715 \exp(-0.072Mf)$$

Figure 10—Marginal ignition probabilities for commercial peat moss. Pineg is the probability of ignition for negative discharges, pipos for positive discharges. Tabular values and simplified equations are given for convenience.

APPENDIX C: A FORTRAN PROGRAM FOR ELECTRIC ARC IGNITION

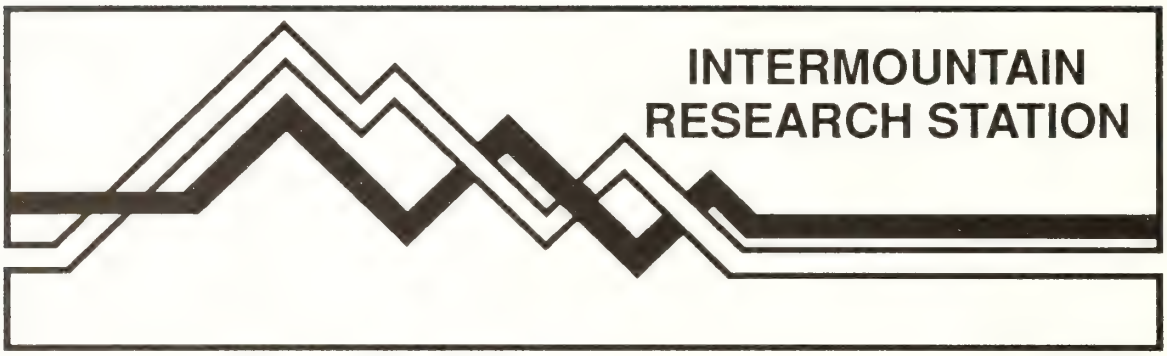
```
C ***********************************************
C
      SUBROUTINE THOR5 (IFUEL,FM,DEPTH,ISTROKE,PROB)
C
C ***********************************************
C
C TO CALCULATE THE MARGINAL IGNITION PROBABILITY GIVEN A NATURAL ELECTRICAL
C DISCHARGE OF TYPE <STROKE> INTO FUEL TYPE <FUEL> WITH MOISTURE
C <FM> % AND/OR DEPTH <DEPTH> IN CM. NOTE THAT NOT ALL NEGATIVE DISCHARGES
C HAVE A CONTINUING CURRENT!!!
C THE SUBROUTINE USES GAUSSIAN QUADRATURE, WITH THE COEFFICIENTS FOR
C THE LAGUERRE POLYNOMIALS FROM:
C     "HANDBOOK OF MATHEMATICAL FUNCTIONS"
C      M. ABRAMOWITZ AND I. STEGUN, EDS.
C      US GOV'T. PRINTING OFFICE, APS-55 1964
C
C THIS PROGRAM IS A PART OF "IGNITION PROBABILITIES FOR WILDLAND FUELS"
C  BY DON LATHAM AND JOYCE SCHLIETER.
C
C !!!!!!DO NOT ALTER ANY NUMBERS IN THIS SUBROUTINE!!!!!!
C
C ***************************************************************
C
C THE INPUT VARIABLE <FUEL> HAS THE VALUE 1-8 ACCORDING TO:
C         1) PONDEROSA PINE LITTER,
C         2) ROTTEN, CHUNKY, PUNKY WOOD,
C         3) PUNKY WOOD POWDER, DEEP (4.8 CM)
C         4) PUNKY WOOD POWDER, SHALLOW (2.4 CM)
C         5) LODGEPOLE PINE DUFF
C         6) DOUGLAS FIR DUFF
C         7) HIGH ALTITUDE, MIXED, MAINLY ENGLEMANN SPRUCE
C         8) PEAT MOSS (COMMERCIAL)
C
C  OTHER FUELS WILL USE ONE OF THESE AS SURROGATE; CONSULT THE
C  ACCOMPANYING TEXT
C
C  THE INPUT VARIABLE <FM> IS THE FUEL MOISTURE IN %
C  THE INPUT VARIABLE <DEPTH> IS THE DUFF DEPTH IN CM.
C  THE INPUT VARIABLE <STROKE> IS +1 FOR POSITIVE DISCHARGES,
C  -1 FOR NEGATIVE DISCHARGES.
C  THE OUTPUT IS <PROB>, THE PROBABILITY OF IGNITION PER DISCHARGE.
C  AGAIN, NOTE THAT ABOUT 1 IN 5 NEGATIVE DISCHARGES HAS A CONTINUING
C  CURRENT. THIS IS ACCOUNTED FOR IN THIS SUBROUTINE.
C
C ***************************************************************
C
C SETUP AND PARAMETERS
C
      DOUBLE PRECISION WT,XI,AC1,AC2,AC3,AC4,B,SUM,T,Y,FX,S
C
C EVERYTHING DOUBLE PRECISION INTERNALLY
C
      DIMENSION WT(6),XI(6),AC1(8),AC2(8),AC3(8),AC4(8),B(8)
C
C
C
C WEIGHTS FOR ORDER 6 POLYNOMIAL
C
      DATA WT/0.458964673950,0.417000830772,0.113373382074,
     +        1.03991974531E-2,2.61017202815E-4,8.98547906430E-7/
C
```

```
C ZEROES OF ORDER 6 POLYNOMIAL
C
      DATA XI/0.222846604179,1.188932101673,2.992736326059,
     +        5.775143569105,9.837467418383,15.982873980602/
C
C EVERY POSITIVE DISCHARGE HAS A CONTINUING CURRENT, ONLY 1 IN 5
C NEGATIVE DISCHARGES DOES.
C
      DATA CCPERPOS,CCPERNEG /1.,0.2/
C
C ONLY TYPE 7 USES BULK DENSITY; WE USE THE AVERAGE FOR THAT FUEL
C
      DATA RHOB /0.127/
C
C COEFFICIENTS FOR THE FUEL TYPES
C
      DATA AC1,AC2,AC3,AC4,B
     +/     0.97, -0.59, 1.2, 0.13, -5.6, -7.1, 0.79, 0.42,
     +    -0.19, -0.15, -0.12, -0.05, 0.0, 0.0, -0.081, -0.12,
     +    0.0, 0.0, 0.0, 0.0, 0.68, 1.4, 0.0, 0.0,
     +    0.0, 0.0, 0.0, 0.0, 0.0, 0.0, -8.5, 0.0,
     +    0.012, 0.005, 0.002, 0.005, 0.007, 0.006, 0.011, 0.005/
C
C
C THESE ARE THE COEFFICIENTS IN THE WEIBULL DISTRIBUTION FOR CC'S
C
      DATA ETANEG,ETAPOS,SNEG,SPOS /1.6,2.3,207.8,69.3/
C
C DETERMINE DISCHARGE TYPE
C
      IF (ISTROKE.EQ.1) THEN
         ETAM=1./ETAPOS
         S=SPOS
         COEF=CCPERPOS
        ENDIF
      IF (ISTROKE.EQ.-1) THEN
         ETAM=1./ETANEG
         S=SNEG
         COEF=CCPERNEG
      ENDIF
C
C CALCULATE F(X) AT XI AND INTEGRATE
C
      SUM=0.0
      DO 100 I=1,6
      T=S*(XI(I)**ETAM)
      Y=AC1(IFUEL)+AC2(IFUEL)*FM+AC3(IFUEL)*DEPTH+AC4(IFUEL)*RHOB
     +  +B(IFUEL)*T
      FX=1./(1.+DEXP(-Y))
  100 SUM=SUM+WT(I)*FX
      PROB=SUM*COEF
C
C
      RETURN
      END
C
C ***********************************************************
C
```

Latham, Don J.; Schlieter, Joyce A. 1989. Ignition probabilities of wildland fuels based on simulated lightning discharges. Res. Pap. INT-411. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 16 p.

Ignition of wildland fine fuels by lightning was simulated with an electric arc discharge in the laboratory. The results showed that fuel parameters such as depth, moisture content, bulk density, and mineral content can be combined with the duration of the simulated continuing current to give ignition probabilities. The fuel state parameters of importance and the ignition probabilities were determined using logistic regression. Graphs, tables, formulas, and a FORTRAN computer program are given for field use.

KEYWORDS: fire ignition, litter, duff, continuing current, logistic regression



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The Intermountain Research Station territory includes Montana, Idaho, Utah, Nevada, and western Wyoming. Eighty-five percent of the lands in the Station area, about 231 million acres, are classified as forest or rangeland. They include grasslands, deserts, shrublands, alpine areas, and forests. They provide fiber for forest industries, minerals and fossil fuels for energy and industrial development, water for domestic and industrial consumption, forage for livestock and wildlife, and recreation opportunities for millions of visitors.

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Department
of Agriculture

Forest Service

Intermountain
Research Station

Research Paper
INT-412

October 1989

Effects of Prescribed Fire on Biomass and Plant Succession in Western Aspen

James K. Brown
Norbert V. DeByle

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THE AUTHORS

JAMES K. BROWN received his bachelor's degree from the University of Minnesota in 1960, his master's degree from Yale University in 1961, and his Ph.D. degree from the University of Michigan in 1968, all in forestry. From 1961 to 1965, he did research on field measurement of fuel properties and fire-danger rating systems while with the Lake States Forest Experiment Station. In 1965, he transferred to the Northern Forest Fire Laboratory, Missoula, MT, where he conducted research on the physical properties, inventory, and prediction of fuels. Since 1979, he has been project leader of a Fire Effects and Use research unit in Missoula.

NORBERT V. DeBYLE (retired), when this work was accomplished, was an ecologist in the Intermountain Research Station's Aspen Ecology and Management research unit in Logan, UT. He now is an associate professor in the Forest Resources Department, Utah State University, Logan. He received a B.S. degree in 1953 and an M.S. degree in 1957 from the University of Wisconsin and a Ph.D. degree in forestry in 1962 from the University of Michigan. While employed with the Intermountain Station from 1961 to 1987, he did research on water yield improvement, fire effects on water and soils, and aspen ecology and management.

RESEARCH SUMMARY

Plant succession and production of biomass were determined for three prescribed fires in aspen (*Populus tremuloides*) and aspen-conifer forests. Forbs and shrubs dominated the understories. Preburn fuel loadings ranged from 19,200 to 56,400 kg/ha. Fires ranged from low to high severity and overstory mortality from 20 to 100 percent. Total fuel consumption alone was poorly related to fire severity. Over 4 postburn years, production of grasses and forbs averaged 1.5 to 3.3 times that of the controls. Maximum production was 2,240 kg/ha, five times that of the associated control. High-severity fire favored forbs over grasses. After 5 years, shrub biomass was 21 to 100 percent of preburn biomass. The proportion of shrub biomass less than 0.5 cm diameter peaked after 2 years. Species responses were varied. Aspen sucker densities peaked during the first 2 postburn years and ranged from one-half to fivefold their preburn densities. Suckering was most prolific following fire of moderate to high severity. The varied patterns of seral vegetation and their management implications are discussed.

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Effects of Prescribed Fire on Biomass and Plant Succession in Western Aspen

James K. Brown
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INTRODUCTION

The widespread quaking aspen (*Populus tremuloides* Michx.) forests in western North America are lightly used for wood products. But they are valued highly as wildlife habitat, for grazing by domestic livestock, as sources of water, and for esthetics and recreation (DeByle 1985). Aspen exists as both a seral and climax species, but it is seral on a majority of sites (Mueggler 1976). Replacement of seral aspen by conifers in the West is gradual and may take 200 to 400 or more years (Bartos and others 1983). This successional process reduces forage production, water yield, and diversity of wildlife habitat (DeByle 1985).

In the past, fire played a prominent role in the perpetuation of aspen forests. Today, however, the existence of seral aspen is threatened by lack of fire in areas of the West (DeByle and others 1987). Prescribed fire offers an economical and environmentally acceptable means of rejuvenating aspen. It can be used successfully if fuel situations and weather conditions are favorable (Brown and Simmerman 1986) and if enough of the overstory is killed (Brown and DeByle 1987). To use prescribed fire effectively, forest managers must know how aspen and understory vegetation will respond to fire of known characteristics. Production of understory vegetation and successional patterns following fire have received only limited study in the western aspen types (Bartos and Mueggler 1981).

This paper reports the results of research undertaken to determine biomass response of seral vegetation and its relationship to fire severity in aspen and mixed aspen-conifer forests.

METHODS

A 120-ha prescribed fire was conducted at Manning Basin northeast of Montpelier, ID, in the Caribou National Forest. Two 1-ha fires were conducted on the Little Bear and Blue Jay drainages north of Kemmerer, WY, in the Bridger-Teton National Forest. Study sites were selected prior to burning to provide a range of surface fuel loadings in aspen and mixed aspen-conifer stands (table 1). Mixed stands were defined as conifers occupying at least 35 percent of the canopy.

At Little Bear and Blue Jay, three square macroplots (30 m on a side) were placed in each stand. Two macroplots were burned, and one remained as the control. At Manning Basin two aspen stands and one mixed stand were burned. Pairs of macroplots were placed in the mixed stand and in the upper elevation aspen stand (U). A single macroplot was placed in the lower elevation aspen stand (L). Single control macroplots for mixed and aspen stands were installed after the fire near the burn perimeter.

Inside the macroplots, 16 subplot centers were permanently located in a uniform grid, with 4 m between the outer subplot centers and the macroplot edge. Subplots varied in size and shape to allow adequate and efficient sampling of downed dead fuels, herbaceous vegetation, shrubs, and small trees. Biomass, cover, and density of understory fuels and vegetation were estimated on the fixed subplots prior to burning. Understory vegetation and ground cover were sampled each year afterwards. Measurements were always taken during the first 2 weeks of August, after peak annual growth of biomass. In addition to the measurements, we made a species list for each macroplot during the annual sampling by a cursory "walk around." Each species was assigned to one of seven cover categories, from only a few plants to more than 75 percent area cover.

Downed woody fuel loadings were determined for 0 to 0.6 cm, 0.6 to 2.5 cm, 2.5 to 7.6 cm, and greater than 7.6 cm diameter classes using the planar intersect method (Brown 1974). Sampling planes were randomly oriented at each subplot. Weights of grasses and forbs were estimated separately on 30- by 60-cm subplots using the weight-estimate method (Hughes 1959; Francis and others 1979). To calibrate ocular estimates of biomass, eight subplots were also systematically located about 2 m outside the macroplot. On these, grass and forb weights were estimated, then clipped, ovendried, and weighed. Forest floor material was sampled on a 30- by 30-cm portion of these subplots also using the weight-estimate method. The forest floor consisted of litter (01 horizon) and some duff (02 horizon), material that would probably undergo flaming combustion and consisting of freshly cast leaves, needles, and other detached plant parts as well as partially decayed material in the upper fermentation layer.

Shrubs, except for myrtle pachistima (*Pachistima myrsinites* [Pursh] Raf.), were sampled by tallying stems by basal diameter classes on 4-m^2 subplots. Biomass was computed using weight versus stem diameter relationships (Brown 1976). To check accuracy of these relationships for first-year sprouts, 30 sprouts for five shrub species were collected and weighed. Comparison of predicted and weighed sprouts showed good agreement for three species and acceptable agreement for the other two. The existing relationships were expected to apply with little

Table 1—Vegetation, fuel, and topographic conditions by stands

Condition	Stand identification				
	Little Bear	Blue Jay	Manning	Manning	Manning
Overstory	Aspen	Mixed	Mixed	Aspen(U)	Aspen(L)
Mean age of dominants (yr)	73	81	102	92	92
Treated plot basal area (m^2/ha)[1]					
Aspen	16	26	8	17	14
Conifer	0.5	13	13	0	0
Treated plot average d.b.h. (cm)					
Aspen	16	16	15	12	15
Conifer	—	18	18	—	—
Community type[2]	POTR/RUOC	POTR-ABLA/ BERE	POTR-PSME/ CARU	POTR/PRVI	POTR/PRVI
Understory fuel[3]	Tall forb	Forb	Forb	Shrub	Shrub
Downed woody fuel	Heavy	Light	Medium	Medium	Heavy
Elevation (m)	2,440	2,440	2,225	2,380	2,225
Aspect	East	East	East	East	East
Slope (percent)	15	15	20	30	20

[1]To convert from m^2/ha to ft^2/acre multiply by 26.6.

[2]Community types conform to classification by Youngblood and Mueggler (1981) and Mueggler and Campbell (1982). Abbreviations are *Populus tremuloides* (POTR), *Abies lasiocarpa* (ABLA), *Pseudotsuga menziesii* (PSME), *Rudbeckia occidentalis* (RUOC), *Berberis repens* (BERE), *Prunus virginiana* (PRVI), and *Calamagrostic rubescens* (CARU).

[3]The classification of understory fuel types was based on amount of shrubs and productivity of herbaceous vegetation (Brown and Simmerman 1986).

error. Weight of myrtle pachistima was determined using estimates of cover and height in a weight algorithm developed by Olson and Martin (1981). In addition to stem counts, seedlings of snowbrush ceanothus (*Ceanothus velutinus* Dougl. ex Hook.) were counted and a subsample weighed. Aspen suckers were tallied in three classes on these 4-m^2 subplots (0 to 0.5 m and 0.5 to 2 m height and 2 m height to 5 cm diameter at breast height [d.b.h.]). Sucker biomass was computed from the stem counts and weight per stem relationships (Bartos and others 1983). All weights were expressed on an ovendry basis. Cover of shrubs, mineral soil, and litter was ocularly estimated on the 4-m^2 subplots. Cover of grasses and forbs was ocularly estimated on the 30- by 60-cm subplots. Conifers less than 3 m tall were tallied on the 4-m^2 subplots. All trees greater than 5 cm d.b.h. were tallied by 5-cm d.b.h. classes over the entire macroplot.

The fire at Blue Jay was ignited thoroughly throughout the plots on August 20, 1981, using a handheld drip torch. Air temperature was 24 °C, and relative humidity was 25 percent. Although fuel moisture content was low (5 to 7 percent fine fuel), the fire failed to spread beyond most points of ignition due to compact litter, sparse fine fuels, and low windspeeds. Some clumps of fuel burned and caused torching of a few subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.) and lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) Duff smoldered for several days in a few small areas, exposing a limited amount of mineral soil.

The fire at Manning Basin was ignited on September 22, 1981, in a line fire pattern using a helicopter drip torch. Moisture content was 8 percent in litter and in 0.6- to 2.5-cm diameter woody material, and 9 percent in woody material greater than 7.6 cm in diameter. Herbaceous vegetation was 40 to 50 percent cured. Temperature was 18 °C and relative humidity was 20 percent. Windspeed varied from 6 to 13 km/h. Fire spread at high intensity into the upper elevation aspen plots but failed to burn in the corner of one plot. At the lower elevation, the flames spread by backing, flanking, and making small headfire runs (fig. 1). Flaming persisted for several minutes due to burnout of large fuels in the lower aspen stand.

The fire at Little Bear was ignited on September 23, 1981, in a line fire pattern using a handheld drip torch. Moisture content was 7 percent for litter and 5 percent for 0.6- to 2.5-cm diameter dead woody material. Herbaceous vegetation was about 50 percent cured. Temperature was 17 °C and relative humidity was 20 percent. Windspeed was mostly 0 to 6 km/h, with gusts to 6 km/h. The fire spread slowly, going out in places at the lower windspeeds, but it spread with a sustained front during the brief wind gusts.

Fuel consumption and fire severity were determined by revisiting the subplots inside macroplots within a few days after burning. Downed woody material was reinventoried along the same transects. Herbaceous vegetation, shrubs, small trees, and litter consumption were ocularly estimated as a fraction of the preburn material that was consumed on each plot. Postburn measurements were taken for 5 years except for herbaceous material, which was heavily grazed in the fifth summer before sampling was possible. Fire severity on each macroplot was rated according to one of the following categories:

Figure 1—Flanking fire at Manning Basin produced flames from 0.5 to 1.5 m in length and effectively killed overstory aspen.

Low—Litter charred but not entirely consumed; shrubs partially killed; less than half of aspen stems killed.

Moderate—Litter consumed, duff deeply charred, but with some remaining charcoal; shrubs killed and partially consumed; most aspen stems charred and appeared killed.

High—Litter and duff completely consumed and mineral soil exposed; shrubs mostly consumed; all aspen stems killed.

Fire severity is a qualitative measure of the total effects of fire on the ecosystem. It reflects mortality to flora and fauna and loss of organic material, which involves the effects of upward and downward heat flux. Upward heat flux, expressed by fireline intensity or flame length, is largely responsible for aboveground plant mortality. Downward heat flux relates to fuel consumption and exposure of mineral soil. It was rated based on a ground char classification by Ryan and Noste (1985). Fuel consumption (table 2), flame length, exposed mineral soil, area burned, and tree mortality (table 3) were measured to help quantify fire severity.

Changes in annual production of herbaceous vegetation due to weather and site variability complicate interpretation of fire effects. To reduce these complications, the data were normalized to productivities of the control plots as a common base. At Little Bear and Blue Jay, site differences between macroplots were adjusted by (1) dividing preburn biomass on burned macroplots by that on control plots, and then (2) dividing all burned macroplot estimates, for all years, by this ratio. Yearly weather differences were adjusted by (1) dividing control postburn biomass for each year by control preburn biomass, and then (2) dividing all burned macroplot estimates for a given year by the ratio for that year. Tables 4 and 5 contain the observed annual production and normalization factors. The postburn adjustment ratios for burned treatments in table 5 are the product of site and weather ratios. The values for control treatments are weather adjustment ratios. As an example of adjustment for site differences, the ratio for grasses at Little Bear was 0.333 (table 5) obtained by dividing 226 by 679 in table 4.

Table 2—Preburn fuel loadings and percentage of preburn fuel consumed by fire

Location	Overstory-understory	Downed woody fuel (cm) 0-0.6	0.6-2.5	2.5-7.6	7.6+	Forest floor	Grass forbs	Shrub	Fines[1]	Total fuel
		Preburn loadings (kg/ha)								
Little Bear	Aspen-forb	[2]150	1,050	7,170	45,710	1,380	900	31	2,130	56,390
Blue Jay	Mixed-forb	590	2,250	3,650	4,260	8,260	46	130	3,020	19,190
Manning	Mixed-forb	530	2,410	5,360	17,590	8,550	330	1,640	4,910	36,410
Manning (U)	Aspen-shrub	450	2,140	5,470	2,760	8,940	490	880	3,960	21,130
Manning (L)	Aspen-shrub	700	3,630	9,360	27,380	10,570	350	1,800	6,480	53,790
		Consumed (percent)								
Little Bear	Aspen-forb	39	14	37	47	67	69	90	40	46
Blue Jay	Mixed-forb	76	75	79	100	18	26	27	72	56
Manning	Mixed-forb	77	67	27	33	66	57	21	52	43
Manning (U)	Aspen-shrub	67	48	32	55	64	82	33	51	52
Manning (L)	Aspen-shrub	93	57	60	93	73	89	68	65	80

[1]Includes 0-2.5-cm downed woody fuel, grass, forbs, and shrubs.
[2]Standard errors of the estimate for preburn fuel loadings on individual macroplots averaged 22 percent of the means for 0-2.5-cm downed woody fuels, 36 percent for large woody fuels, 13 percent for forest floor, 28 percent for herbs, and 20 percent for shrubs.

Table 3—Predominant flame length of propagating fire front, net mineral soil exposed by fire, percentage of macroplot burned, percentage of aspen and conifer trees killed, and fire severity class

Location	Overstory-understory	Plot No.	Predominant flame length	Mineral soil	Area burned	Year 1 mortality	Severity
			m	*Percent*			
Little Bear	Aspen-forb	4	0.1-0.3	10	37	19	Low
	Aspen-forb	5	0.1-0.3	12	40	3	Low
Blue Jay	Mixed-forb	10	0-0.1	1	19	20	Low
	Mixed-forb	11	0-0.1	1	18	18	Low
Manning	Mixed-forb	50	0.2-1.0	34	60	20	Moderate
	Mixed-shrub	51	0.2-1.0	21	57	53	Moderate
Manning (U)	Aspen-shrub	52	1-5	44	78	85	High
	Aspen-shrub	53	1-5	22	72	41	Moderate
Manning (L)	Aspen-shrub	54	0.5-1.5	33	91	99	High

Table 4—Observed production of grasses and forbs

Location	Stand	Treatment	Year from fire P	1	2	3	4
			- - -

At Manning Basin, two problems added difficulty to interpreting the data. We were unable to install control plots prior to burning, and preburn sampling was done in September when an unknown quantity of forbs had cured and disintegrated, particularly in the lower elevation stands. However, grass biomass was still intact. Thus, forb production was adjusted only for yearly weather, but grass production was adjusted for both site and weather. To adjust for site differences, production on control macroplots was assumed to be the average production on those macroplots over the 4 postburn years. This seemed appropriate because production and growing season precipitation were unrelated in the postburn data. Thus, the average postburn production should be a reasonable estimate of the preburn production.

RESULTS

Preburn fuel loadings ranged from 19,200 to 56,400 kg/ha (table 2). (Pounds per acre are 89 percent of kilograms per hectare, so these units are similar for many considerations.) Data were combined for paired macroplots because preburn loadings and consumed fuel quantities were similar. The large difference in loadings among stands was primarily due to downed woody material greater than 7.6 cm in diameter (large fuel). Downed woody fuel loadings less than 7.6 cm diameter (small fuel) for the mixed/forb and aspen/shrub stands were similar to fuel loadings found in a variety of conifer types in the Northern Rocky Mountains (Brown and See 1981). But loading of downed woody fuel less than 2.5 cm diameter was very low in the Little Bear aspen/forb stand.

The sampled forest floor fuel quantities were primarily from the upper 2 cm of forest floor and consisted of litter and some duff (table 2). In separate measurements, the total duff layer averaged 36,500 kg/ha in the mixed controls at Blue Jay and 47,300 kg/ha at Manning. In the aspen control plots, total duff averaged 7,780 kg/ha at Manning and was nearly nonexistent at Little Bear. In a related study, quantities of litter averaged only about 1,900 kg/ha and were similar for aspen and mixed stands (Brown and Simmerman 1986). Except for the Manning mixed/forb stand, which contained high shrub loadings, the herbaceous and shrub fuel loadings were low compared to a classification of similar fuel types (Brown and Simmerman 1986). Based on this same classification, probability of successfully applying prescribed fire was moderate in the stands with forb understories and high in the shrub understories.

Fire Severity and Mortality

At Little Bear, the fire spread primarily in grass and forbs supported by newly fallen leaves (400 kg/ha). Fire severity rated low, even though approximately 21,500 kg/ha of large woody fuels were consumed. In spite of a heavy preburn fuel loading, 53 percent of the large fuels remained unburned because insufficient woody fuel less than 2.5 cm diameter was available to ignite the large woody pieces, which averaged 16 cm in diameter. The burnout time of grass was too short to ignite much of the woody material. The lack of woody fuels less than 2.5 cm diameter hinders flammability where aspen overstories and forb understories dominate because aspen crowns produce little fine-sized branchwood. At Blue Jay, even though fire severity was low, most of the woody fuels were consumed because they were concentrated in a few patches of subalpine fir. All patches of fuel were hand ignited.

At Manning Basin, fire severity rated moderate to high mainly because the fire spread well, consuming large quantities of forest floor and killing much of the aboveground vegetation. Shrubs were a significant component of fine fuel consumption that largely determines fireline intensity and flame length. Rapid ignition using jelled gasoline dropped by helicopter accounted for the large flames in the upper aspen stand. Considering all treatments, large fuel and total fuel consumption were not a good indicator of fire severity. Area burned and consumption of forest floor and fine fuels related most closely to fire severity (tables 2 and 3).

After 3 years at Little Bear, 21 percent of the aspen had died on the treated plots. Mortality continued, and after 5 years it was approximately twice the mortality on the control macroplot (table 6), which averaged 3.5 percent annually. Although the fire at Little Bear killed aspen, the effect on apical dominance was probably small because considerable live aspen remained to produce auxin.

The first year after fire at Blue Jay, a much greater proportion of conifers had died than aspen. But after 3 years, 40 percent of the aspen had died, exceeding the mortality rate of conifers. After 5 years, an even greater percentage of aspen and conifers had died, with small changes on the controls (table 6).

At Manning, 85 percent or more of the aspen had died after 3 years on the treated macroplots, and after 5 years nearly all of the aspen had died. All aspen were dead 1 year after fire in only one stand. In the mixed stand, about 30 percent of the conifers were killed but mortality was not apparent until the second year after fire. A major shift in the overstory occurred in the mixed stand where density of conifers, predominantly Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), increased from 48 to 93 percent of the total tree density (table 6).

Small conifers (<5 cm d.b.h.) were reduced from 5,000 to 2,000 per hectare, with mortality occurring over a 4-year postburn period in the mixed stand at Blue Jay. Similarly, two-thirds of the few small conifers in the mixed stand at Manning were killed. Small conifers were absent in the other stands.

Table 6—Change in stand density of live aspen and conifers greater than 5 cm d.b.h. from preburn to 1 and 5 year postburn periods based on a 100 percent inventory

Location	Stand	Treatment	Year from fire			Change from preburn to	
			Preburn	1 yr	5 yr	1 yr	5 yr
			Trees per hectare			*Percent*	
			Aspen				
Little Bear	Aspen	Burned	739	677	445	–8	–40
	Aspen	Control	655	—	536	—	–18
Blue Jay	Mixed	Burned	1,184	996	652	–14	–45
	Mixed	Control	1,184	1,161	978	2	–17
Manning	Mixed	Burned	413	138	15	–66	–96
	Mixed	Control	—	712	506	—	[1]–29
	Aspen(U)	Burned	1,497	544	79	–64	–95
	Aspen(L)	Burned	326	0	0	–100	–100
	Aspen	Control	—	1,107	699	—	[1]–42
			Conifers				
Blue Jay	Mixed	Burned	376	245	240	–35	–36
	Mixed	Control	319	363	363	+14	+14
Manning	Mixed	Burned	326	306	193	–6	–41
	Mixed	Control	—	835	647	—	[1]–22

[1] Change from postburn year 1 to year 5.

Grasses and Forbs

Fire stimulated grass and forb production in both aspen and mixed overstory types (fig. 2). In the treated stands, production of herbaceous vegetation over the 4-year postburn period averaged 1.5 to 3.3 times more than the control plots. Production during postburn year 1 ranged from 0.9 to 3.6 times that of the controls. Overall, burning doubled production over the 4 postburn years. The greatest increase in production occurred during the second postburn year. Averaged over 4 years, the percentage of herbaceous biomass comprising forbs increased substantially following fire at Manning Basin (from 8 to 52 percent for the mixed stand and 22 to 59 percent for the aspen stands). But the percentage of grass was increased at Little Bear (21 to 40 percent) and at Blue Jay (9 to 22 percent).

Grass production was substantially greater in the aspen than in the mixed stands (fig. 2). Maximum production in aspen was 4.5 times that in the mixed stands. Nevertheless, the greatest increase relative to controls occurred in the mixed stand at Blue Jay, where preburn production was meager. Although fire severity was low at Blue Jay, increased light from a reduced canopy may have aided a strong response. Coverage of grass increased slightly from preburn to postburn year 4 in all treated stands. Robust growth and extensive flowering of pinegrass (*Calamagrostis rubescens* Buckl.) accounted for the strong early postburn response of grass in the lower Manning aspen.

Average production of forbs during all postfire years was three times greater in the aspen stands than in the mixed stands. Forb production generally increased but not with any consistent pattern. The largest responses were in years 2 and 3 at Manning. Because forb production at Manning could not be adjusted for site differences between controls and treated plots, the relative change in production due to fire was probably underestimated. Average coverage of forbs increased from 12 percent in the preburn year to 30 percent in postburn year 4 for the aspen stands and from 4 to 20 percent for the mixed stands.

The relative decrease in postfire forb production in the Little Bear aspen stand (fig. 2) appeared to be caused by a large increase in pocket gopher activity compared to the control. Dense pocket gopher populations can reduce forb production (Teipner and others 1983). Maximum forb production was more than five times that of the control in postburn year 2 at the Manning upper aspen stand. Most of the production was from wild hollyhock (*Iliamna rivularis* [Dougl.] Greene), a species absent in preburn vegetation (fig. 3). It grew tall (2 m) and dense and dominated the site for several seasons. Biomass of wild hollyhock was sampled near the upper aspen stand where it was dense and lush. It averaged 2,260 kg/ha during postburn year 2 and 940 kg/ha in year 3. By year 4, biomass of wild hollyhock had declined further and its foliage appeared considerably more chlorotic. By postburn year 6, it had almost disappeared. It displayed great capacity to reestablish from dormant seed in the soil following fire.

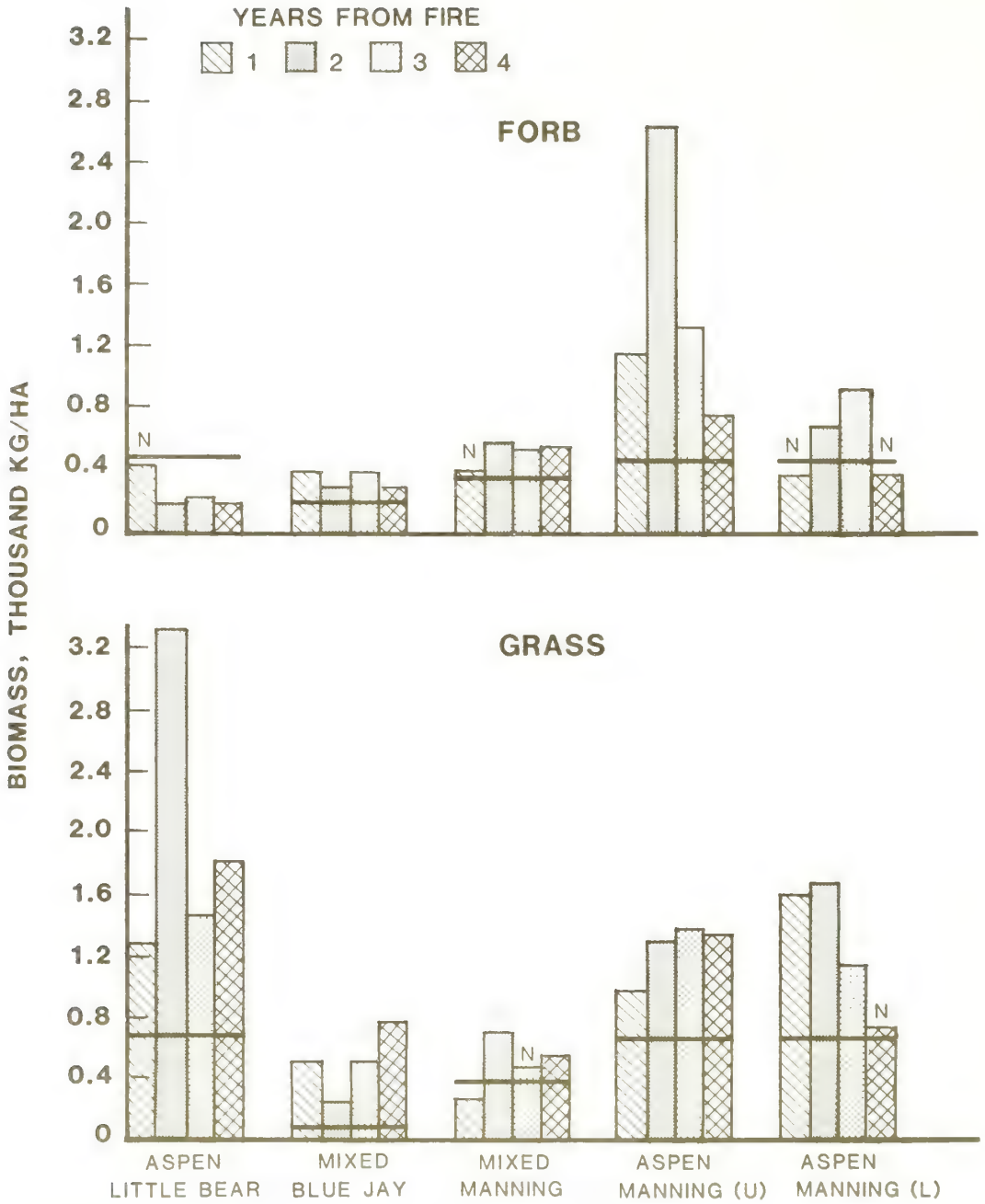

Figure 2—Adjusted biomass production of forbs and grasses following fire. Production of controls is shown by a horizontal line. Standard errors of estimates expressed as a percentage of mean production averaged 18 percent for grasses and 14 percent for forbs. An N placed above a bar means that the control and treatment were not significantly different based on a paired comparison t-test at the 90 percent confidence level. Otherwise, treatments and controls differed significantly.

Figure 3—One week (A) and 1 year (B) after fire at Upper Manning Basin. Wild hollyhock (*Iliamna rivularis*) dominates the postburn vegetation.

By sampling density of seed pods and seeds per pod, number of seeds produced in year 2 was estimated at 14,300 per square meter. In a study of mature forest seedbanks in central Idaho (Kramer and Johnson 1987), density of wild hollyhock was 1,470 per square meter, the largest stored seed density in a single stand among 80 species.

The response of forbs to fire at Manning was similar to that found by Bartos and Mueggler (1981) in a Wyoming aspen stand with a forb-dominated understory. There, common fireweed (*Epilobium angustifolium* L.) increased dramatically in some areas, similar to the response of wild hollyhock on our sites. They found that grass production decreased the first year following fire, then increased; whereas we observed grass production to increase the first year. After a high-intensity prescribed fire in a central Idaho Douglas-fir stand, Lyon (1971) reported that wild hollyhock and common fireweed dominated vegetal cover until postburn year 6. Besides the striking appearance of wild hollyhock, false dragonhead (*Dracocephalum parviflorum* Nutt.) appeared as an important species in the aspen-conifer mix after fire. It appeared as a rosette in 1982, flowered in 1983 (year 2), and then faded away through years 1984 through 1986. Likewise, woodland strawberry (*Fragaria vesca* L.) occupied more than 5 percent cover in the burned mixed plots; it endures fire (Rowe 1983) and may be competitive in the postfire community. Common fireweed and duncecap larkspur (*Delphinium occidentale* Wats.) were not evident before burning but after burning became important species in the aspen plots, perhaps as invaders. Table 7 lists important species by cover class.

Table 7—Understory vascular plant species that provided more than 5 percentage cover on at least one macroplot by coverage classes

Species	Aspen-conifer mixed forest				Pure aspen forest			
	Untreated	Year 2	Year 4	Location[1]	Untreated	Year 2	Year 4	Location[1]
Grasses and Sedges								
Agropyron caninum	[2]2		2	B,M	2	2	2	L,M
Bromus carinatus	1	1	1	B,M	2	2	2	L,M
Calamagrostis rubescens	4	4	3	M	3	3	2	M
Carex geyeri	2	2	2	M	2	2	2	M
Carex microptera and *hoodii*				B	2	2	2	L,M
Elymus glaucus	2	3	3	B,M	3	3	4	L,M
Phleum pratense						2	1	L
Poa pratensis	2			B	2	2	1	L
Forbs								
Achillea millefolium	1	2		B,M	2	2	1	L,M
Arnica cordifolia	3	3	2	B,M		2	1	L,M
Aster engelmannii	2	2	1	B,M	3	2	2	M
Aster foliaceous					2	2	1	L,M
Astragalus miser	2			B				
Balsamorhiza macrophylla	2	1	1	B	1	2	1	L
Castilleja miniata	2	2	2	M	2	2	1	M
Collomia linearis		1		B	1		2	L
Delphinium occidentale						2	2	M
Dracocephalum parviflorum		2		B,M		1		M
Epilobium angustifolium		1	1	B,M		2	1	M
Frageria vesca		2	2	M				L,M
Geranium viscosissimum	3	3	2	B,M	2	3	2	L,M
Iliamna rivularis	1	2	1	B,M		3	2	L,M
Lupinus spp.	2	2	2	B,M		2	2	L,M
Osmorhiza chilensis	2	2	2	B,M	2	2	1	L,M
Osmorhiza occidentale	1			B	2	3	1	L,M
Perideridia gairdneri					2	2	1	L,M
Polygonum douglasii					2	1	1	L,M
Pyrola secunda	2	1		M				
Rudbeckia occidentale					3	2	2	L
Sidalcea oregana						2	1	L
Solidago canadensis					2	2	1	L,M
Thalictrum fendleri	2	2	2	B,M	2	3	2	L,M
Wyethia amplexicaulis	2	1	2	B	1	1	1	L
Shrubs								
Amelanchier alnifolia	2	2	2	B,M	4	2	2	M
Berberis repens	2	2	2	B,M	3	2	2	M
Ceanothus velutinus	3	2	2	M	3	2	2	M
Pachistima myrsinites	3	1	2	B,M	3	1	1	M
Prunus virginiana	2	2		M	3	2	2	M
Rosa nutkana and *woodsii*	2	1	2	B,M	2	2	2	M
Shepherdia canadensis	3	2	2	B				
Symphoricarpos oreophilus	2	2	1	B,M	3	2	1	L,M

[1]B = Blue Jay; L = Little Bear; M = Manning Basin.

[2]Percentage cover of individual species was condensed from the original seven categories into the following classes:

1 = 5 percent or less, but more than a few plants
2 = 6 to 25 percent
3 = 26 to 50 percent
4 = 51 to 75 percent

No species occupied more than 75 percent cover. The untreated observations were recorded for control plots in all years and treatment plots in the preburn year. The year 2 and year 4 postburn observations were recorded for treatment plots.

Shrubs

Shrub response at Manning Basin was varied (table 8). In the mixed stand, biomass of shrubs increased slowly; it was only 31 percent of preburn biomass after 5 years. Biomass in the mixed stand control also increased during these same years, mainly myrtle pachistima. Other shrub species in the control decreased, suggesting that factors other than fire may have affected shrub response in the burned mixed stand. In the upper aspen stand, biomass was 66 percent of the preburn quantity after 5 years. Yearly fluctuations in stem density and biomass suggested that growth and mortality of new stems occurred in a dynamic, irregular process. In the lower aspen stand, which initially had high shrub cover, biomass exceeded the preburn level after the third growing season and remained about the same through the fifth season. After 5 years, shrub canopy was 60 to 80 percent of preburn coverage (table 8).

Based on the rate of recovery, both cover and biomass should reach preburn conditions within 5 to 10 years after fire, which is similar to recovery of shrub forage yields for other shrub communities (Wright 1972). All species were root crown shrubs except creeping barberry (*Berberis repens* Lindl.), which is rhizomatous; thus, all species were capable of sprouting, making rapid recovery of shrubs likely. At Little Bear and Blue Jay, biomass and cover of shrubs were initially low and remained that way. Increases in biomass were nonsignificant (table 8). Thus, the low-severity fire did not appear to influence shrub response.

The proportion of biomass containing foliage and stemwood less than 0.5 cm in diameter increased on all burned plots for 2 years following fire, then slowly decreased. It remained about 10 percent higher than on the control plots over the 5 postburn years. Thus, during this period a greater proportion of the shrub biomass was of a size desired by browsing animals.

Some individual species responded consistently and others varied among the stands at Manning Basin. Biomass of Saskatoon serviceberry (*Amelanchier alnifolia* Nutt.), known to resprout strongly after fire (Noste and Bushey 1987), recovered to preburn quantities within 3 years in the lower aspen stand and within 5 years in the mixed stand (table 9). After 5 years, it was only half of its preburn biomass in the upper aspen stand. Intense competition by wild hollyhock may have slowed its recovery. Where black chokecherry (*Prunus virginiana* var. *melanocarpa* [Nels.] Sarg.) was well established before fire in the lower aspen stand at Manning, its postburn biomass exceeded preburn biomass in two seasons and was twice preburn biomass after five seasons (table 9). In the other stands, where it was a minor component, it responded slowly.

In the aspen stand, biomass of snowbrush ceanothus increased substantially by sprouting. In the mixed stand, the density of sprouted stems was about half of preburn density, but biomass was considerably less than preburn levels. Some mortality to snowbrush ceanothus and the long time needed to regrow clumps of large diameter stems that existed before fire accounts for its slow recovery in the mixed stand. Also, some snowbrush ceanothus plants were killed by the fire, as has been observed in other burns (Noste 1985). A flush of snowbrush ceanothus seedlings appeared the first year after fire. Seedling density decreased markedly by the second year, but a much smaller decrease occurred after that (table 10). The increase in seedlings from the third to fourth growing

Table 8—Cover and accumulated shrub biomass before (P) and after fire accompanied by coefficients of variation and tests of significance

Location	Overstory-understory	Cover			Biomass year from fire						CV[2]	Year comparisons[1]		
		P	3	5	P	1	2	3	4	5		P:1	P:5	1:5
		Percent			kg/ha						Percent			
Fire Treatments														
Little Bear	Aspen-tall forb	5	3	3	32	15	21	33	27	20	67	NS	NS	NS
Blue Jay	Mixed-forb	9	9	12	127	197	113	126	243	188	21	NS	NS	NS
Manning(U)	Aspen-shrub	34	15	28	881	303	237	309	479	535	19	0.05	0.05	NS
Manning(L)	Aspen-shrub	56	29	42	1,807	220	841	1,984	1,662	1,833	25	0.05	NS	0.05
Manning	Mixed-forb	23	12	14	[3]707	263	238	206	275	218	25	NS	0.10	NS
Controls														
Little Bear	Aspen-tall forb	2	3	1	8	—	0	10	6	10	92	NS	NS	NS
Blue Jay	Mixed-forb	23	19	25	232	—	421	703	715	504	23	NS	NS	NS
Manning	Aspen-shrub	—	42	65	—	1,178	1,386	1,771	1,307	1,376	23	NS	NS	NS
Manning	Mixed-forb	—	33	27	—	646	792	923	733	909	38	NS	NS	NS

[1]An analysis of variance with years as treatments and Tukey's hsd test were performed to test for differences in biomass between selected years. Significance probabilities exceeded by the tests are given; NS is nonsignificant.

[2]CV = 100 (std. error/mean) for biomass averaged over all years.

[3]One outlier, a subplot that fell on an unusually large-stemmed slump of *Ceanothus velutinus* was eliminated. When included, the mean was 1,639 kg/ha.

Table 9—Biomass of individual shrub species 5 years after fire and its percentage of preburn biomass (in parentheses) for the fire treatments at Manning Basin

Species	Stand					
	Mixed		Aspen(U)		Aspen(L)	
	kg/ha					
Amelanchier alnifolia	84	(100)	289	(46)	512	(101)
Berberis repens	47	(60)	93	(65)	47	(85)
Ceanothus velutinus	151	(14)	74	[1](4,720)	269	(216)
Pachistima myrsinites	53	(25)	12	(46)	81	(9)
Prunus virginiana	8	(4)	24	(60)	228	(138)
Rosa spp.	8	(94)	24	(307)	27	(58)
Salix scouleriana	0		0		668	[1](1,910)
Symphoricarpos oreophilus	<1	(21)	7	(40)	0	

[1]The percentages are extremely high owing to small amounts of preburn biomass.

Table 10—Average number of snowbrush ceanothus (*Ceanothus velutinus*) seedlings per hectare and percentage frequency of occurrence on subplots at Manning Basin

Stand	Statistic	Year after fire			
		1	2	3	4
Mixed	Number	26,600	9,800	3,600	6,100
	Frequency	31	28	19	25
Aspen (U)	Number	25,500	13,100	9,000	12,300
	Frequency	47	50	50	44
Aspen (L)	Number	7,700	3,600	3,400	1,900
	Frequency	38	38	19	25

seasons suggests that germination of new seedlings occurred over several years. But the data are too limited to confirm this. Seedling biomass was included in the analysis although it was a minor component until 4 years after fire. Average seedling weight was 1.45 g in postburn year 3 and 4.80 g in year 4. By year 6, snowbrush ceanothus was beginning to dominate vegetal cover over major portions of the Manning burn.

Biomass of Scouler willow (*Salix scouleriana* Barratt) sprouts increased dramatically in the lower aspen stand, but no seedlings were observed. Biomass of myrtle pachistima increased slowly over the 5 postburn years in all stands. It was greatly reduced in the lower aspen stand. Coverage of myrtle pachistima was reduced substantially but should recover based on observed sprouting and seedlings.

Although creeping barberry is a small plant, it responded quickly after fire and increased its proportion of total shrub biomass in all stands. After 5 years, biomass was approximately two-thirds of preburn quantities. Biomass of Nootka rose (*Rosa nutkana* Presl.) or Woods rose (*R. woodsii* Lindl.) recovered to near preburn quantities by the second postburn year and fluctuated after that.

Aspen Suckers

Sucker response varied among the stands probably owing to differences in fire severity, vigor of clone, and postburn plant competition (fig. 4). Postburn sucker densities peaked in either the first or second postburn year and declined from peak levels by factors of 0.2 to 0.5 to their fifth year densities. Peak postburn densities ranged from nearly 0.5 to 5.0 times preburn densities.

Sucker densities remained low, up to a maximum of 3,000 per hectare, following low-severity fire. At Little Bear, densities declined from preburn levels on both control and treated plots. This stand appeared to be deteriorating even before fire. At Blue Jay, densities increased from none before fire to a small number after fire. But the remaining substantial overstory of aspen and conifers discouraged sucker development.

Following moderate- to high-severity fire at Manning, peak sucker densities ranged from 17,000 to 39,000 per hectare and were within the range of densities reported for other fires in western aspen (Bartos 1981; Brown and DeByle 1987; Patton and Avant 1970). The different patterns of response are worth noting. In the mixed

stand, sucker numbers decreased significantly from preburn densities, but biomass of suckers increased steadily from postburn year 1 (fig. 4). Thus, even though fewer suckers existed after fire, aspen may have benefited because conifer cover was reduced and suckers were growing into the spaces previously occupied by conifers.

In the upper aspen stand, suckers increased by fivefold the second year then declined to 2,860 per hectare in postburn year 5, which was less than the preburn density. Although suckers declined markedly to a rather low density, sucker biomass was almost twice that of preburn biomass, indicating that aspen trees would establish an overstory. In the lower aspen stand, many suckers existed before fire because the stand had been opened up by earlier heavy snow breakage that encouraged suckering. Even so, postburn sucker densities were nearly double that of preburn numbers in year 1, then declined to less than preburn numbers in year 5. But biomass was 914 kg/ha by year 5, which slightly exceeded preburn amounts. In this case, only 6 percent of the suckers exceeded 2 m in height, yet accounted for 37 percent of the biomass. In all of the Manning stands, the proportion of suckers exceeding 0.5 m in height was greater in year 5 than before fire (fig. 4).

Although production of herbaceous vegetation increased in all treated stands, the pattern of early vegetal succession varied. Accumulated understory biomass of herbs, shrubs, and suckers peaked in year 1 where fire severity was low (fig. 5A, B) and in year 2, 3, and 4 where fire severity was moderate to high. Peaking of accumulated biomass primarily reflected fluctuations in production of herbaceous vegetation. The aspen stands in the Manning burn showed two early successional patterns, domination in one by herbs (fig. 5C) and the other by woody plants (fig. 5D). In the stand dominated by woody plants, 67 percent of the woody biomass was shrubs and 33 percent was aspen suckers. These percentages held for preburn vegetation and in postburn years 3 and 4. Thus, the aspen-shrub stands returned rapidly to the preburn proportions of shrubs and suckers. The early successional pattern in the mixed stand (fig. 5E), dominated by a woody understory before fire, indicated a slower postburn recovery to domination by woody plants.

In a study of vegetation recovery following a large wildfire in mixed conifers, seral patterns also varied considerably, ranging from long-lasting herb stage to rapid regrowth of shrubs that dominated herbs (Stickney 1986). Varied patterns of seral vegetation following fire occur commonly within individual burns.

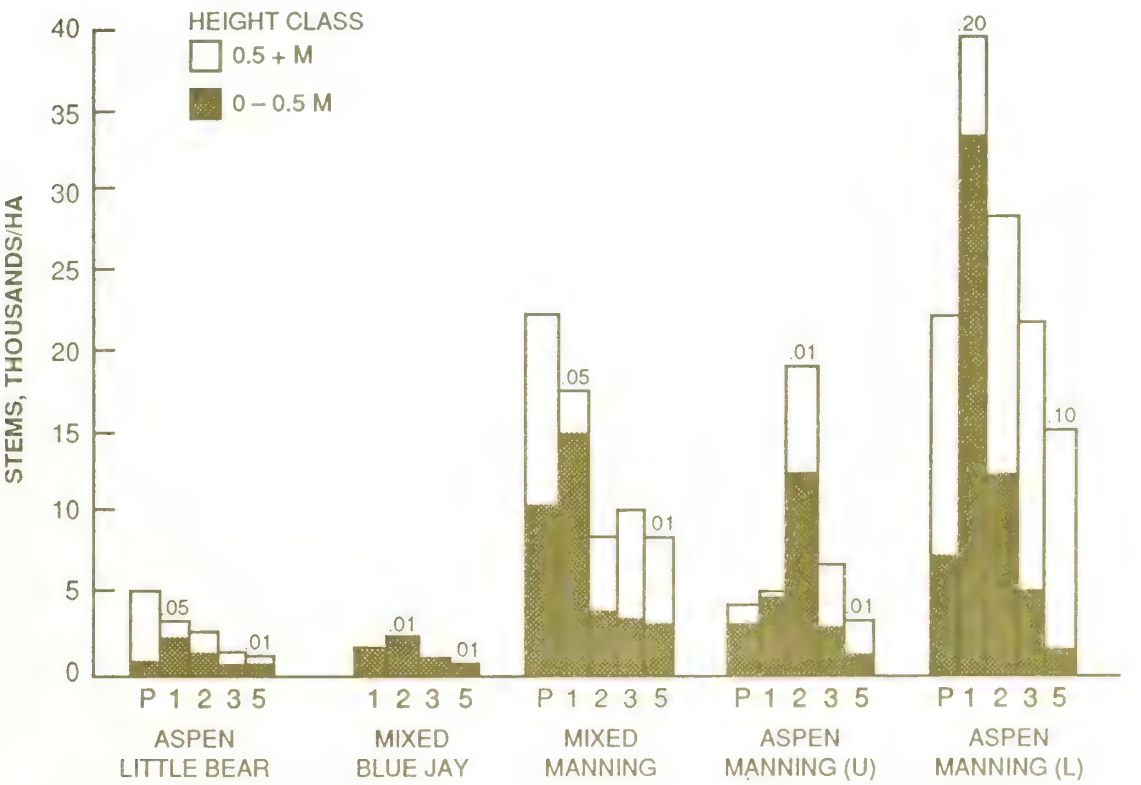

Figure 4—Density of aspen suckers by height class for preburn (P) and postburn years 1, 2, 3, and 5. Few suckers exceeded 2 m in height, so they were included in the 0.5+-m class. No preburn suckers were observed at Blue Jay. Sucker counts were not normally distributed. A logarithmic transformation of the differences in total sucker density between years was normally distributed. A paired comparison t-test on these differences between preburn and postburn peak density and between preburn and postburn year 5 density was performed. The values above the bars are the significant difference confidence levels.

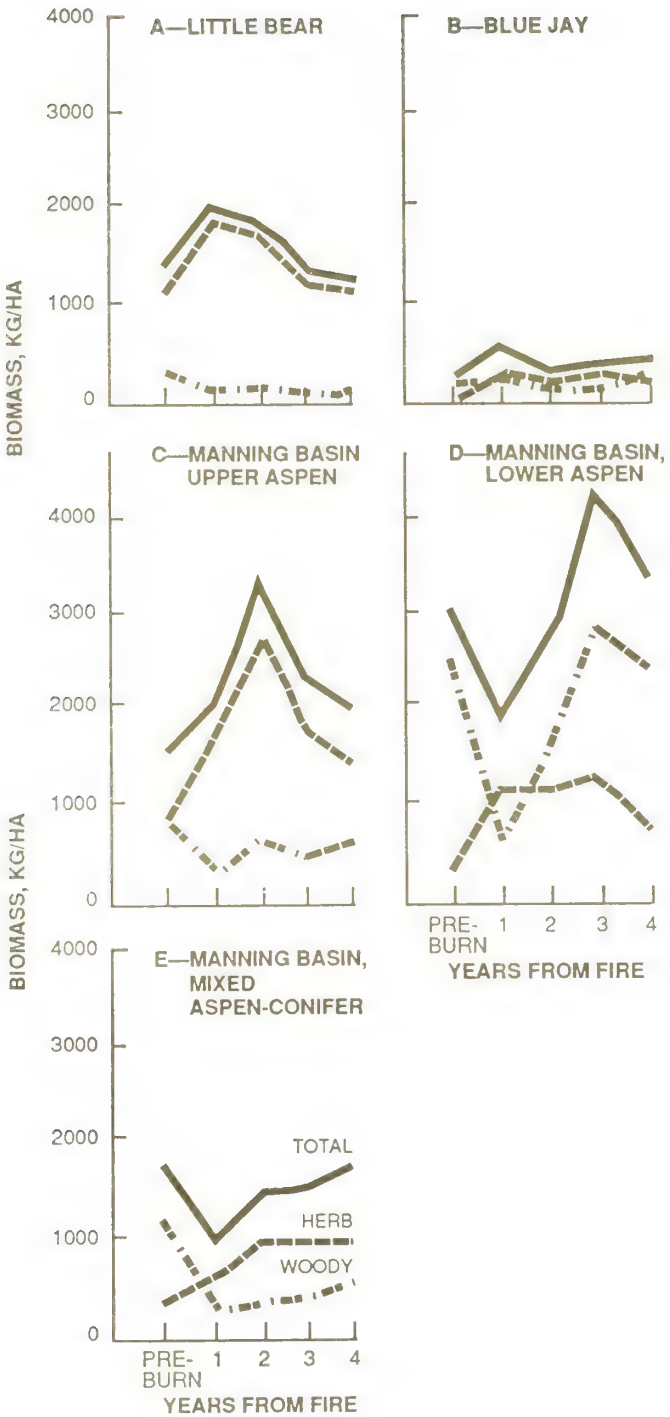

Figure 5—Accumulated biomass of herbaceous vegetation (unadjusted) and woody plants (shrubs and aspen suckers) before and after fire in five stand categories.

Almost all species present before fire were adapted to survival as endurers (Rowe 1983) capable of resprouting from belowground organs. Our findings agreed with the conceptual model of Lyon and Stickney (1976) that a majority of species on site before fire will reestablish and that dominating species will establish in 1 year. But the model suggests little about the structure of vegetation that can vary greatly. In one of four stands, for example, no extant plants of wild hollyhock were present on the site before fire, but it dominated the postburn vegetation for 3 years.

DISCUSSION AND CONCLUSIONS

Fire severity appeared to influence the composition of herbaceous vegetation. The proportion of forbs increased on plots receiving high severity treatment and decreased on plots receiving low severity fire. However, separating the influences of fire severity and preburn plant composition on postburn composition was not possible. Fire severity appeared to have little effect on herbaceous biomass in that all burns responded with increased production relative to controls.

Low-severity fire had little measurable effect on cover and biomass of shrubs. Moderate- to high-severity fire at Manning induced varied regrowth of shrubs. For example, sprouting of snowbrush ceanothus was considerably less in the mixed stand, where some large plants were killed. Mortality may have been caused by consumption of an excessive buildup of leaf litter that caused prolonged downward heating around the root crowns. Species that sprout from root crowns are more vulnerable than those that sprout from farther below the soil surface. Effects of heat on individual plants can vary considerably within moderate and high severity fires because of localized burning conditions.

Abundant aspen suckers were produced in the moderate- to high-severity fire. Sucker response to low-severity fire was poor, perhaps for several reasons: (1) too few aspen were killed by fire, (2) competition from an overstory of aspen and conifers remained, and (3) one stand appeared to be in poor health. Killing a high proportion of aspen trees should favor suckering because apical dominance is reduced and sucker-stimulating cytokinins are increased in the roots (Schier 1981). A strong relationship between suckering and fire severity was not demonstrated here nor previously (Brown and DeByle 1987), probably because other factors that are difficult to separate from fire severity such as parent stand vigor, density of aspen root systems, soil characteristics, clonal characteristics, and competition with other vegetation also influence sucker response. Early postfire sucker response can vary greatly, but large numbers of suckers are probably not necessary to establish new stands of

aspen where management is primarily for range and wildlife resources. Following fire, high sucker densities decline considerably over the first 5 years, while initial low densities decline little (Bartos 1981; Brown and DeByle 1987). In mixed stands the most important factor affecting redevelopment of aspen following fire is probably reduced conifer competition.

Determination of the effects of fire severity on postfire vegetation response was hampered in this study, as it is in field studies generally, because the fire treatment is only one factor influencing postfire responses. Other factors influencing prediction of postburn vegetation response are (1) prefire vegetation, (2) species adaptations to fire, (3) environmental conditions, and (4) chance (Lyon and Stickney 1976; Morgan and Neuenschwander 1985; Rowe 1983). The complexity of vegetation response is illustrated by the aspen stands at Manning that had high fire severity. One species, wild hollyhock, which germinated from seed stored in the soil, dominated the upper stand but was absent from the lower stand. The preburn plant community appears to be the most important factor. It can have a greater effect on understory vegetation response than intensity (Armour and others 1984) and severity of surface fires. Because many factors influence recovery of postfire vegetation, some owing to chance, variable vegetation responses should be expected to fires of the same severity and intensity.

For applying prescribed fire, this study supports the need to choose good opportunities for achieving sustained spread of fire. Dead woody fuels less than 2 cm diameter are needed to help ignite larger woody fuels and to provide adequate flame residence time to kill aspen. Shrubs contribute significantly to good burning opportunities (Brown and Simmerman 1986). Prescribed fires of moderate to high severity are needed to assure sustained spread and sufficient mortality to the overstory (Brown and DeByle 1987). If the conifer component cannot be reduced with prescribed fire, managers should augment the fire with cutting. Land managers should expect varied response in suckers, shrubs, and herbaceous vegetation during early postfire years.

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Biomass of grasses, forbs, shrubs, and aspen suckers was determined annually for three prescribed fires in aspen and aspen-conifer forests in southeastern Idaho and western Wyoming. Fires ranged from low to high severity and overstory mortality from 20 to 100 percent. Over 4 postburn years, production of grasses and forbs averaged 1.5 to 3.3 times that of controls. After 5 years, shrub biomass was 21 to 100 percent of preburn biomass. The varied patterns of seral vegetation and their management implications are discussed.

KEYWORDS: fire severity, understory vegetation

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Small Mammal Populations in a Grazed and Ungrazed Riparian Habitat in Nevada

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RESEARCH SUMMARY

Community composition and relative abundance of small mammal populations were compared between an aspen (*Populus tremuloides*)/willow (*Salix* spp.) riparian habitat seasonally grazed by cattle and a comparable adjoining habitat protected from grazing for the previous 11 years by an exclosure. The exclosure, constructed in 1977, is on the West Fork of Deer Creek in northeastern Nevada. Small mammal populations were compared by removal trapping over a 5-day period in late summer 1988.

Four species accounted for 82 percent of the total number of individual animals trapped. These were deer mouse (*Peromyscus maniculatus*), western jumping mouse (*Zapus princeps*), least chipmunk (*Tamias minimus*), and Great Basin pocket mouse (*Perognathus parvus*).

Other small mammals trapped either irregularly or in smaller numbers on the study site included golden-mantled ground squirrel (*Spermophilus lateralis*), vagrant shrew (*Sorex vagrans*), long-tailed vole (*Microtus longicaudus*), montane vole (*Microtus montanus*), Townsend's ground squirrel (*Spermophilus townsendii*), northern pocket gopher (*Thomomys talpoides*), and bushy-tailed woodrat (*Neotoma cinerea*).

Estimated density of small mammals was over a third higher in the ungrazed habitat as compared to the grazed area. Small mammal standing crop biomass, species richness, and species diversity were 3.24, 1.83, and 1.25 times higher, respectively, on the ungrazed site. Each of the 11 species recorded during the study was trapped inside the protected area. Only six species were trapped in the grazed habitat. The grazed study site did not appear to have received excessive use by cattle in recent years compared to nearby riparian habitats.

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Small Mammal Populations in a Grazed and Ungrazed Riparian Habitat in Nevada

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INTRODUCTION

Small mammals constitute a major part of wildlife communities in riparian habitats. They may fill important roles in ecosystem function (Sieg 1988). Small mammals have significant influences on vegetation and soils, exert predatory pressure on insects and other small mammals, and provide an important prey base for mammalian, reptilian, and avian predators. Small mammals are among the least studied and most poorly understood taxonomic groups in the riparian habitat (Szaro 1988).

Riparian ecosystems are sensitive to livestock grazing. Grazing by cattle can alter the structure and composition of riparian plant communities (Kauffman and Krueger 1984). Alterations in vegetational features may, in turn, affect the quality of the riparian habitat for small mammals (Kauffman and others 1982; Moulton 1978). The effects of grazing are amplified in the geographically limited riparian landscapes of the arid and semiarid West.

We compare community composition and the relative abundance of small mammal populations between a riparian habitat grazed by cattle and a comparable adjacent area protected from grazing for the previous 11 years by a large (100+ acres) fenced exclosure. The exclosure, constructed in 1977, is on the West Fork of Deer Creek in northeastern Nevada. Small mammal populations were compared by removal trapping during late summer 1988.

STUDY AREA

The Deer Creek study site is 34 miles north of Wells in Elko County, NV, at an elevation of about 6,200 ft. It is near the southern boundary of the Columbia Plateau (Fenneman 1931) in the Salmon Falls Creek drainage. The Great Basin lies immediately south. West Fork of Deer Creek originates from springs and flows in a narrow, V-shaped canyon cut in mid-Tertiary rhyolitic rock. Soils are generally fine-textured; depths range from shallow on steep residual slopes to deep on relatively level alluvial fans and floodplains (Platts and others 1988).

Average annual precipitation at Wells (elevation 5,650 ft) is about 10 inches, with peaks in May and June and November and December. Mean annual snowfall is 60 inches. The growing season is short, averaging less than 100 days at Wells. Warm days and cool nights provide a large difference in daily high and low temperatures (U.S. Department of Commerce 1970).

Eight major and several minor vegetation community types were identified in the riparian zone and adjoining upland (Platts and others 1988). For our study, we consolidated the community types into six general categories based on similarities in vegetational composition and structure:

Kentucky bluegrass (*Poa pratensis*)
Willow (*Salix* spp.)/mesic herbaceous
Big sagebrush (*Artemisia tridentata*)/Kentucky bluegrass
Big sagebrush/upland
Aspen (*Populus tremuloides*)/mesic herbaceous
Aspen/big sagebrush

The stream is closely bordered by clumped communities of aspen, willow, and other deciduous shrubs including common chokecherry (*Prunus virginiana*), golden currant (*Ribes aureum*), redosier dogwood (*Cornus stolonifera*), and Woods rose (*Rosa woodsii*). Slender wheatgrass (*Agropyron trachycaulum*), Kentucky bluegrass, Baltic rush (*Juncus balticus*), field horsetail (*Equisetum arvense*), and common dandelion (*Taraxacum officinale*) are common grasses and forbs.

The gallery-like riparian zone is isolated from similar arboreal vegetation by a surrounding mosaic of upland shrub habitats dominated by sagebrush and including rubber rabbitbrush (*Chrysothamnus nauseosus*), Woods rose, bush oceanspray (*Holodiscus dumosus*), antelope bitterbrush (*Purshia tridentata*), and mountain snowberry (*Symphoricarpos oreophilus*). Cheatgrass (*Bromus tectorum*), basin wildrye (*Elymus cinereus*), Sandberg bluegrass (*Poa secunda*), tansymustard (*Descurainia* spp.), and white stoneseed (*Lithospermum ruderale*) are common associates.

Floodplains with dead and downed aspen are common both inside and outside the exclosure. These remnants of aspen/mesic herbaceous communities were once flooded by beaver impoundments that killed the aspen. Although washed-out dams are still evident, there is no current evidence of beaver activity.

The 11,555-acre Deer Creek pasture, located largely on public lands under the jurisdiction of the Bureau of Land Management, U.S. Department of the Interior, has an estimated grazing capacity of 2,495 animal unit months (AUM's). Records indicate that during the 1960's and 1970's, seasonal (May through September) stocking levels were about 4,000 to 5,000 AUM's. Historic grazing levels were much higher (Crispin 1981). Recent stocking has varied from about 2,300 to 4,100 AUM's with a grazing season from about mid-July to mid-November (table 1).

Table 1—Livestock grazing summary for the 11,555-acre Deer Creek pasture, Nevada, 1978 to 1988[1]

Year	Season of use	Animal unit months	Type of livestock
1978	7/15-11/29	2,680	Yearlings, cows, bulls
1979	7/16-11/22	4,140	Cows, bulls
1980	8/07-10/19	2,310	Cows, bulls
1981	7/12-10/10	2,800	Cows, bulls
1982	No information	No information	No information
1983	8/09-11/15	3,150	Cows
1984	8/01-10/09	2,310	Cows, bulls
1985	7/15-10/10	2,720	Cows, bulls
1986	7/17-10/15	2,990	Cows
1987	8/16-11/15	2,600	Cows, bulls
1988	7/19-10/25	2,780	Cows, bulls

[1]From Phillips (1989).

METHODS

The rectangular cattle exclosure, about 3,200 ft long and of variable width, is oriented lengthwise along the West Fork. Two 2.8-acre trapping grids, one in the upper section of the exclosure and the other in the adjoining (upstream) unprotected area, were established to estimate small mammal populations. The trapping grids were placed near the center of larger (22.5-acre) plots established to census bird populations (Medin and Clary in press). Grazed and ungrazed plot locations were carefully selected on the basis of topographic and vegetational similarities. Forty trapping stations were located and marked in both the grazed and ungrazed habitats. Ten stations were placed at 82-ft intervals along two parallel trapping lines on each side of the stream. The inner lines were placed near the edge of the stream; the outer lines were placed 82 ft from the stream.

Two Museum Special mouse traps and one Victor rat trap were placed near each station. Traps were baited with a mixture of peanut butter and rolled oats and examined daily for 5 consecutive days from July 20 to 24, 1988.

Vegetation and other features of the grazed and ungrazed areas were measured from August 15 to September 2, 1988. A 50- by 50-cm (0.25-m^2) quadrat was located at each of 12 systematically positioned sample locations in each vegetation community type-treatment combination for a sample size of 72 per treatment. (All plot dimensions used in the study were in metric units.) Canopy cover (Daubenmire 1959) was ocularly estimated for the total of each plant life form (graminoid, forb, shrub) and recorded as the midpoint of one of eight percent cover classes (0-1, 1-5, 5-10, 10-25, 25-50, 50-75, 75-95, 95-100). Percentages of litter, rock, bare ground, and lichen-moss were similarly estimated. The vegetative height (excluding flower and seed-head heights) of each graminoid, forb, and shrub nearest the center of each quadrat was recorded.

Biomass of graminoids, forbs, and small shrubs was estimated by clipping vegetation from ground level upward within a vertical projection from the 0.25-m^2 quadrats. Clipped materials were bagged, ovendried, and weighed. A 3- by 3-m (9-m^2) plot, concentric to each 0.25-m^2 quadrat, was used to sample biomass of large and medium shrubs. Basal diameter, maximum height, and species were recorded for each shrub stem rooted within the plot. Equations provided by Brown (1976) were used to estimate shrub biomass.

Height and diameter at breast height (d.b.h.) were recorded for each tree stem rooted within 10- by 10-m (100-m^2) plots that were concentric to each 0.25-m^2 quadrat. Biomass of downed woody material was sampled midway between vegetation sample plots. The methods followed Brown (1974) except that slope corrections were not made and there were no measures of litter or duff depth.

Scientific and common names of small mammal species follow Jones and others (1982). Authorities for plant names are in Welsh and others (1981).

RESULTS AND DISCUSSION

Few structural (physiognomic) differences in vegetation existed between the grazed and ungrazed sites on Deer Creek. Eleven species of small mammels were trapped on the study sites.

Vegetation

The most evident structural difference was in the herbaceous layer where graminoid biomass and graminoid and forb height values were reduced on the grazed site (table 2). Graminoid biomass on the grazed plot was only about half that inside the exclosure. Shrub biomass, mostly willows, was not significantly different on the grazed and ungrazed sites. Estimates of graminoid, forb, and shrub canopy coverage were similar on the grazed and ungrazed areas. The relatively larger standard deviation (SD) of the shrub biomass component on the ungrazed area suggests more structural variability in that vegetation factor on the protected plot.

Tree density, including all size classes, was 442 stems per acre on the ungrazed plot and 415 stems per acre on the grazed plot (table 2). Aspen was the only tree species found on the study area. Patches of live aspen of various

Table 2—Vegetation and other features of grazed and ungrazed study plots, Deer Creek, Nevada, 1988

Item	Ungrazed		Grazed		
	$\bar{x}$[1]	SD	$\bar{x}$[1]	SD	Probability[2]
Graminoid					
Biomass (lb/acre)	1,538	1,135	806	621	< 0.001
Canopy cover (%)	50.5	21.7	49.4	22.6	766
Height (ft)	1.2	.5	.8	.7	< .001
Forb					
Biomass (lb/acre)	135	147	127	131	716
Canopy cover (%)	7.1	8.8	6.8	9.2	.842
Height (ft)	.5	.4	.4	.4	.068
Shrub					
Biomass (lb/acre)	15,275	87,207	12,090	30,229	.770
Canopy cover (%)	6.7	13.3	6.9	13.2	.928
Height (ft)	4.0	3.4	4.4	3.9	.542
Tree					
Density (n/acre)	442	608	415	818	.819
Diameter (inches)	2.6	1.5	3.0	3.0	.230
Height (ft)	19.4	10.8	22.3	17.7	.241
Other					
Downed woody (lb/acre)[3]	45,182	33,066	71,413	50,722	<.001
Bare ground (%)	10.4	18.5	11.6	14.6	.666
Litter (%)	26.1	19.3	23.1	17.4	.329
Rock (%)	5.4	14.6	8.1	18.4	.331
Lichen-moss (%)	1	9	< .1	4	.606

[1] $N = 72$.
[2] Probabilities associated with unpaired *t*-tests. Small probabilities suggest a significant difference between grazed and ungrazed areas.
[3] Dead twigs, branches, stems, and boles of trees and shrubs that have fallen and lie on or above the ground.

size classes were irregularly distributed along the stream and sometimes on adjacent residual slopes. Single stems and occasional broken stumps of standing dead aspen were scattered throughout the riparian zone. A single stand of large aspen trees on the grazed area tended to inflate average values of tree diameter and height on the grazed plot.

Downed woody material, mostly the result of earlier beaver activity in the drainage, was more abundant on the grazed plot. Most of the downed woody material was aspen tree boles and branches strewn crosswise throughout much of the riparian zone. Other features of the two areas, including estimates of bare ground, rock, and litter coverage, were similar.

The grazed study site did not appear to have received excessive use by cattle in recent years compared to other riparian habitats in the general locality. The exclosure, placed across the riparian zone and including the steep adjacent uplands of the V-shaped canyon, may function as a drift fence that restricts the normal movement of cattle along the stream.

Small Mammals

The 11 species of small mammals trapped on the study site were:

vagrant shrew (*Sorex vagrans*)
least chipmunk (*Tamias minimus*)
Townsend's ground squirrel (*Spermophilus townsendii*)
golden-mantled ground squirrel (*Spermophilus lateralis*)
northern pocket gopher (*Thomomys talpoides*)
Great Basin pocket mouse (*Perognathus parvus*)
deer mouse (*Peromyscus maniculatus*)
bushy-tailed woodrat (*Neotoma cinerea*)
montane vole (*Microtus montanus*)
long-tailed vole (*Microtus longicaudus*)
western jumping mouse (*Zapus princeps*)

Of these, deer mice, western jumping mice, least chipmunks, and Great Basin pocket mice accounted for 82 percent of the total number of individual animals caught. Other species were trapped irregularly or in smaller numbers. Five species, including Townsend's ground squirrel,

northern pocket gopher, bushy-tailed woodrat, montane vole, and long-tailed vole, were trapped only in the ungrazed habitat.

The total number of small mammals trapped was larger in the protected area when compared to the grazed area (table 3). Estimated density was over a third higher in the ungrazed habitat. Further, small mammal standing crop biomass, species richness, and species diversity values were higher inside the exclosure. Each of the 11 species recorded during the study was trapped in the protected area. Only six species were trapped in the grazed habitat.

Deer Mouse—The deer mouse was the most often trapped small mammal in both the grazed and ungrazed habitats (table 3). Naive density (Johnson and others 1987) was only slightly higher on the ungrazed plot. Most of the deer mice were trapped in the big sagebrush/upland community type adjacent to the riparian zone. A few were trapped in each of the other community types sampled. The deer mouse is one of the most widespread and generalized of all North American rodents (Baker 1968). Overall, deer mice are probably Nevada's most abundant mammal (Hall 1946). They are found in a wide variety of habitats including swamps, waterways, forests, grasslands, and deserts, and among rocks and cliffs (Larrison and Johnson 1981). Thomas (1979) assigned the deer mouse a high habitat versatility rating with respect to its reproduction and feeding orientation. It occupies a variety of plant successional stages (Thomas 1979).

Others have reported contradictory results when comparing the abundance of deer mice in grazed versus ungrazed habitats. Kauffman and others (1982) found more deer mice in eastern Oregon riparian habitats after late-season grazing (late August to mid-September) than in ungrazed riparian habitats. But by late summer of the following year, and before grazing, the species composition of small mammal communities was not significantly different between grazed and ungrazed plots. Similarly, Moulton (1978) found a positive response by deer mice to grazing in a cottonwood (*Populus sargentii*) riparian habitat in eastern Colorado. Samson and others (1988) also found deer mouse densities consistently higher on grazed pastures before and after the introduction of winter grazing by cattle in an eastern Colorado cottonwood floodplain habitat. Conversely, Rucks (1978) reported fewer deer mice in grazed versus ungrazed riparian communities in the Gunnison Basin of southwestern Colorado.

Table 3—Relative abundance, naive density, diversity, and other attributes of small mammal populations on grazed and ungrazed study plots, Deer Creek, Nevada, 1988

Species	Foraging guild[1]	Relative abundance (*n*/100 trap nights)		Naive density[2] (*n*/acre)	
		Ungrazed	Grazed	Ungrazed	Grazed
Vagrant shrew (*Sorex vagrans*)	INS	0.3	0.8	0.7	1.8
Least chipmunk (*Tamias minimus*)	OMN	0.8	0.2	1.8	0.4
Townsend's ground squirrel (*Spermophilus townsendii*)	OMN	0.2	0.0	0.4	0.0
Golden-mantled ground squirrel (*Spermophilus lateralis*)	OMN	1.2	0.2	2.5	0.4
Northern pocket gopher (*Thomomys talpoides*)	HER	0.2	0.0	0.4	0.0
Great Basin pocket mouse (*Perognathus parvus*)	GRA	0.2	0.7	0.4	1.4
Deer mouse (*Peromyscus maniculatus*)	OMN	5.0	4.2	10.8	9.0
Bushy-tailed woodrat (*Neotoma cinerea*)	HER	0.2	0.0	0.4	0.0
Montane vole (*Microtus montanus*)	HER	0.2	0.0	0.4	0.0
Long-tailed vole (*Microtus longicaudus*)	HER	0.3	0.0	0.7	0.0
Western jumping mouse (*Zapus princeps*)	OMN	2.8	2.3	6.1	5.0
Total naive density (*n*/acre)				24.6	18.0
Total standing crop biomass (g/acre)				1,121	346
Species richness (*n*)				11	6
Species diversity ($1/\Sigma p_i^2$)[3]				3.62	2.89

[1]After Martin and others (1951). INS = insectivore, GRA = granivore, HER = herbivore, OMN = omnivore.
[2]After Johnson and others (1987). Effective trapping area and grid size are assumed to be identical.
[3]After Hill (1973).

Western Jumping Mouse—Jumping mice were commonly trapped in both grazed and ungrazed habitats (table 3). Most were trapped in streamside habitats with the frequency of capture highest in the Kentucky bluegrass, willow/mesic herbaceous, and aspen/mesic herbaceous community types. Rucks (1978) in Colorado and Hanley and Page (1982) in Nevada trapped the western jumping mouse only in ungrazed plant communities. Jumping mice are inhabitants of the boreal life zone in Nevada (Hall 1946). They occur most commonly adjacent to streams in alder (*Alnus* spp.), aspen, or willow habitats where moist soils support a heavy growth of herbaceous vegetation (Larrison and Johnson 1981; Linsdale 1938). Clark (1971) trapped the western jumping mouse most often in the lowland aspen community type; most were captured within 164 ft of standing water.

Least Chipmunk—More least chipmunks were trapped in the ungrazed area than in the grazed (table 3). Nearly all were caught in the big sagebrush/upland community type. The smallest of Nevada chipmunks, the least chipmunk occupies mostly sagebrush habitats from the lowest to the highest elevations (Hall 1946). They also occur in black greasewood (*Sarcobatus vermiculatus*) communities at low elevations (O'Farrell and Clark 1986). In Idaho, the species exhibits two divergent habitat preferences; one the sagebrush biome, and the other, the open forest and juniper areas of parts of southern Idaho (Larrison and Johnson 1981). It was given a low habitat versatility rating in the Blue Mountains of eastern Oregon and Washington (Thomas 1979). In northeastern California and northwestern Nevada, the least chipmunk responded negatively to grazing in dry habitats and positively to grazing in moist habitats (Hanley and Page 1982).

Great Basin Pocket Mouse—Naive density of the pocket mouse was over three times higher on the grazed plot than on the ungrazed plot (table 3). The pocket mouse was most commonly trapped in the big sagebrush/upland community type. Although this is a species of arid and semiarid habitats (Larrison and Johnson 1981), Linsdale (1938) trapped pocket mice adjacent to streams, on wet ground, and in *Microtus* runways, and suggested that the species is not restricted entirely to arid or semiarid environments. O'Farrell and Clark (1986) found the Great Basin pocket mouse among the most abundant small mammals in extensively grazed sagebrush habitats in northeastern Nevada. Hanley and Page (1982) reported a positive response by Great Basin pocket mice to grazing in mesic habitats—Nevada bluegrass (*Poa nevadensis*) /sedge (*Carex* spp.) and aspen in northeastern California and northwestern Nevada.

Other Species—Several other species of small mammals were trapped on the study site (table 3). Most of the golden-mantled ground squirrels were caught in the ungrazed habitat. All were trapped in big sagebrush/upland communities. Of these, most were caught near rock slides or clifflike rock outcrops that occurred with greater frequency in the protected area. Vagrant shrews were trapped infrequently in both grazed and ungrazed habitats. All were caught near the stream in Kentucky bluegrass communities. Incidental numbers of the Townsend's ground squirrel, northern pocket gopher, bushy-tailed woodrat, montane vole, and long-tailed vole were trapped. Each of these mainly herbivorous species was trapped only in the ungrazed area (table 3). The voles were caught in both the Kentucky bluegrass and aspen/mesic herbaceous community types.

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Small mammal populations were compared between a grazed habitat and a comparable adjoining habitat protected from grazing by an exclosure. Composition, naive density, standing crop biomass, species diversity, and other attributes of the small mammal communities were assessed. More species and higher numbers of most small mammals were found in the ungrazed habitat.

KEYWORDS: density, biomass, diversity, *Peromyscus maniculatus*, *Zapus princeps*, *Tamias minimus*, *Perognathus parvus*

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MTCLIM: A Mountain Microclimate Simulation Model

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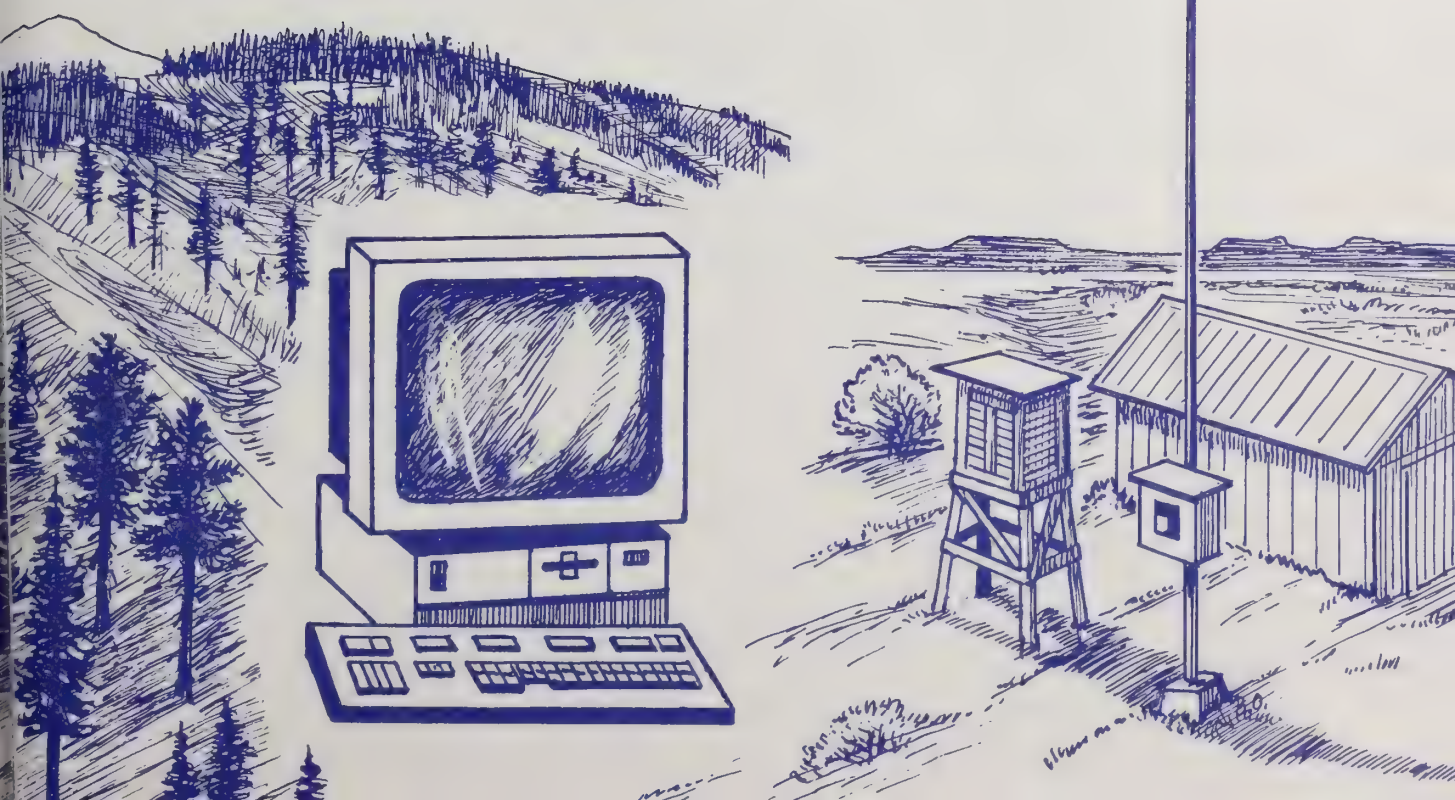

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RESEARCH SUMMARY

The MTCLIM model predicts daily solar radiation, air temperature, relative humidity, and precipitation for mountainous sites by extrapolating data measured at National Weather Service stations. The model may be used to generate data for use in fire models, ecological models, insect and disease models, or developing silvicultural prescriptions. Potential applications are discussed in this paper.

This paper gives the rationale for the MTCLIM model and describes how to execute the model. Preparation of input, adjustment of coefficients, and interpretation of output are discussed. MTCLIM is available on the Forest Service's Data General System and on IBM and IBM-compatible systems.

Evaluation of model outputs (solar radiation, air temperature, relative humidity, and precipitation) are presented by comparing MTCLIM-predicted data with observed data. These tests were run using observed data from up to nine different sites not used in developing the model. Results of these evaluations show that MTCLIM predicts daylight average and maximum air temperatures with an accuracy of 4 °F (r^2 >0.86) and minimum temperatures with an accuracy of 6 °F (r^2 >0.56). Predictions of solar radiation are accurate to 100 W/m^2 (r^2 >0.50) and relative humidity to 11 percent (r^2 >0.43). Precipitation predictions are accurate within 0.15 inches (r^2 >0.49) when two base stations are used. Adjustments to coefficients are discussed relative to these evaluations and how the values might be changed to reflect different conditions from the Northern Rocky Mountains where MTCLIM was developed.

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MTCLIM: A Mountain Microclimate Simulation Model

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INTRODUCTION

This paper presents the logic and equations of a mountain microclimate simulator (MTCLIM) that is designed to extrapolate routine National Weather Service (NWS) data to adjacent mountainous terrain. Typically, meteorological data are measured at city airports in valley bottoms and are not available for mountainous terrain.

Other papers (Running and Hungerford 1983; Running and others 1987) have reported on initial tests of extrapolation and the use of MTCLIM for ecological modeling. Originally the model was designed to interface with ecological models, but we have restructured some parts to make it useful for other purposes. This paper presents the modifications and results of further testing by comparing model outputs with observed data. We also describe how to use the model, including some specific applications.

The paper is divided into the following sections:

1. Description of MTCLIM and the model components.
2. Executing MTCLIM, including a description of inputs and outputs tailored for Data General and IBM-PC systems.
3. Evaluation of the model outputs using predicted vs. observed regression analysis.
4. Applying MTCLIM as a management tool.

DESCRIPTION OF MTCLIM

Base Station Inputs

The mountain microclimate simulator (MTCLIM) extrapolates meteorological variables from a point of measurement (referred to as the "base" station) to the study "site" of interest, making corrections for differences in elevation, slope, and aspect between the base station and the site. The first step in using MTCLIM is to determine the appropriate synoptic meteorological database. The Forest Service, U.S. Department of Agriculture, National Fire Danger Rating System (NFDRS) (Furman and Brink 1975) has an extensive network of stations throughout the forested region of the Western United States, but operates only during the summer fire months. Remote Automated Weather Stations (RAWS) are being established in mountainous areas throughout the West, but the data are not routinely available to users outside the Federal agencies (Warren and Vance 1981), and many operate only during the summer months. Another source, and the one we used in developing MTCLIM, is the Climatological Data summary compiled by the National Oceanic and Atmospheric Administration (NOAA), National Climatic Center, Asheville, NC. These stations, operated by the National Weather Service (NWS), are usually located at major airports.

Data for NWS stations are compiled monthly for each State, giving daily air temperature and precipitation at secondary stations; and dewpoint, cloud cover, sunshine duration, windspeed, and other variables at major airport stations. MTCLIM uses vertical (elevation-related) corrections to extrapolate from NWS stations to

adjacent mountainous sites. Accuracy of extrapolation decreases as distance (horizontal) between a base station and study site increases, because of changes in air masses, cloud cover, and precipitation. Selection of representative base stations is discussed in the section describing creation of input files.

Model Components

A flowchart of the model components of MTCLIM is shown in figure 1. Daily meteorological data are received from the base station. Input requirements are daily maximum and minimum air temperature and precipitation. Dewpoint is used if available. Site topographic factors are then required for the site for which meteorological data are to be extrapolated. These site factors and base station data are then used by MTCLIM to predict incoming solar radiation, air temperature, humidity, and precipitation at the site (fig. 1). The details of the procedure will be discussed for each of the subroutines.

Definition of Variables

Typically in climatic work, 24-hour averages, totals, and maximum and minimum values have been used to express solar radiation, air temperature and humidity, and precipitation. Because a major objective of building this model was to provide inputs to ecological models for predicting plant growth, we defined daylength in terms of the plant processes affected. For example, daylength for photosynthesis and transpiration is more exactly defined as the period of time when the light compensation point is exceeded, rather than sunrise to sunset. We have set this light compensation point at 70 W/m^2 in this model. Thus, daily total radiation can be calculated for either this truncated daylight period or the sunrise to sunset period. The sunrise to sunset period can result in a daylength 20 percent longer than the truncated daylength.

Rather than the typical average temperature (max-min + 2), we have used a daylight average temperature, which is the average temperature from sunrise to sunset. Many of the physiological processes of plants are more closely related to the daylight period. Calculation of daylight average temperature will be discussed under the air temperature subroutine. In addition, maximum and minimum temperature are calculated. The daylight period is also used for the relative humidity parameter.

Time Scales of Prediction

The time scale of MTCLIM is daily, chosen mainly because synoptic data are most readily available in this form. Additionally, we have found a 1-day time step to be an appropriate compromise for ecological modeling between the higher resolution hourly time steps that require large climatic data files (Knight and others 1985; Running 1984b), and longer time scales, weekly, monthly, or yearly, that progressively average out climatic fluctuations and miscalculate hydrologic partitions of the ecosystem (Nemani and Running 1985). For some uses, however, weekly, biweekly, or even monthly time steps may be adequate. Data for longer time steps can be obtained from MTCLIM by running the model for the daily time step and then averaging the output for the desired period.

Units of Measurement

Maximum flexibility is provided by allowing for input data for the base station and output data to be expressed in English units (°F, inches, etc.) or the International System (SI) units (°C, centimeters, etc.). In addition, days can be expressed as a Julian date or by month and day. Details for specifying the desired units are discussed in the sections describing creation of the input and output files.

Description of Subroutines

The four meteorological variables predicted by MTCLIM: air temperature, incoming solar radiation, humidity, and precipitation are calculated by separate subroutines. We do not consider wind conditions, partly because energy and gas exchange by conifer needles is insensitive to windspeed beyond a rather low threshold (i.e., 5 cm/s) (Smith 1980), and partly because general climatological principles for extrapolation in mountains are not available.

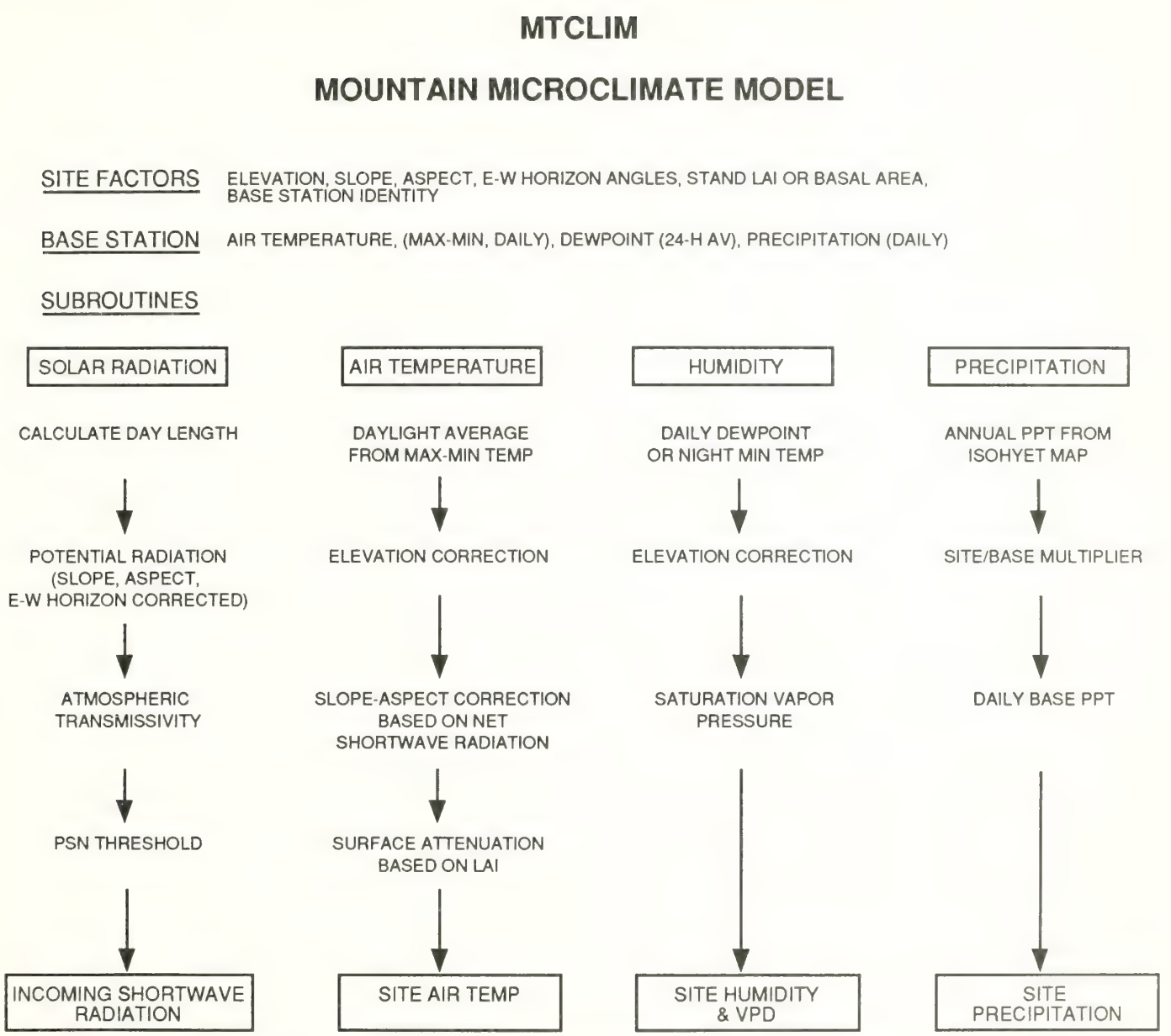

Figure 1—Flowchart of the MTCLIM model for estimating daily microclimate conditions in mountainous terrain. The site factors and base station variables shown are required inputs for the model.

Solar Radiation—Estimating daily incoming solar radiation proved to be difficult because most NWS stations in Montana do not directly measure incoming radiant energy. NWS data collected are from semiquantitative "sunshine recorders" or qualitatively from observers' cloud cover estimates. After attempting to work with these data to estimate incoming solar radiation (Running and Hungerford 1983; Satterlund and Means 1978), we decided to use the algorithm of Bristow and Campbell (1984) that relates diurnal air temperature amplitude to atmospheric transmittance. Their analysis requires only daily maximum and minimum air temperatures and precipitation. This algorithm (see appendix D) appears to be accurate, having been tested on three sites ranging from maritime to continental climates and accounting for 70 to 90 percent of the variability in daily incoming radiation on these sites. We first compute clear sky transmissivity for the elevation of the site of interest, assuming clear sky transmittance at mean sea level is 0.65, and increasing 0.008/m of elevation. Final atmospheric transmissivity is then calculated as an exponential function of diurnal temperature amplitude of the base station (Bristow and Campbell 1984). This procedure accounts for clouds, water vapor, pollutants, and other atmospheric factors that reduce clear sky transmissivity.

Next, a potential radiation model derived from the logic of Garnier and Ohmura (1968), Buffo and others (1972), and Swift (1976) is used to calculate direct and diffuse solar radiation. This model accounts for site differences in latitude, slope, and aspect, and it truncates the direct beam solar irradiance by east and west horizons, rather than assuming a flat horizon. Potential above-atmosphere radiation is reduced by calculated atmospheric transmissivity to produce a final estimate of incoming solar radiation for the site. The potential radiation model is also run for an equivalent flat surface at the site elevation to generate a ratio of flat surface to slope radiation absorbed. This ratio is used for adjusting air temperature estimates at the site. Finally, the daylength is computed by the radiation submodel for each day. Daylength is computed either for sunrise to sunset or for the period that incoming solar radiation exceeds a threshold of 70 W/m^2. This is a threshold for conifer stomatal opening, transpiration, and positive net photosynthesis (PSN) used to describe the operational environment of trees (Jarvis and Leverenz 1983). This threshold number can be easily changed for different types of vegetation and produces an operational day length approximately 85 percent of sunrise to sunset. If this threshold is not invoked, total sunrise to sunset solar radiation is computed. Details of the transmissivity and radiation subroutines are shown in appendix D and the MTCLIM code (appendix A).

Air Temperature—Daylight average air temperature is estimated by assuming the diurnal temperature trace to be a sine form, with the maximum and minimum points given by data from the base station. Integrating the sine function over three quadrants (Parton and Logan 1981) yields the following equation for daylight weighted average air temperature:

$$T_{ave} = \text{TEMCF} * (T_{max} - T_{mean}) + T_{mean} \quad (1)$$

where:

T_{ave} = weighted average daylight air temperature
T_{mean} = arithmetic mean $(T_{max} + T_{min}) \div 2$ for a day
TEMCF = coefficient to adjust daylight average temperature.

Details of the sine form assumption are shown in appendix B.

Daylight average air temperature is then corrected for elevation using a general lapse rate of 3.5 °F/1,000 ft for summer, reduced by 10 percent on clear days, and increased by 10 percent on cloudy days (Finklin 1983). This lapse rate is close to published values (3.0 to 4.0 °F/1,000 ft) for western mountains (Baker 1944;

Finklin 1983, 1986). The classification of clear and cloudy days is based on the ratio of potential to actual radiation as computed by the model. Days that have ratio values less than 0.5 are treated as cloudy. The ratio of slope/flat surface radiation computed in the radiation submodel is used as a multiplier to adjust air temperature for differences between slopes receiving different radiant energy inputs.

This simple approach increases the air temperature on a south-facing slope and decreases temperature on a north-facing slope relative to a flat surface at the same elevation. But the magnitude of the temperature differential is a function of the characteristics of the energy exchange surfaces of the slopes (McNaughton and Jarvis 1983). Bare slopes can have maximum surface temperature differentials exceeding 18 °F (Parker 1952), but closed canopy forests may exhibit virtually no slope-related differences in surface temperature when the surface is an actively transpiring canopy (Kaufmann 1984; Sader 1986). Consequently, the predicted temperature is adjusted by a multiplier based on the leaf area index of the study site. For example, if a south-facing surface of LAI = 1.0 receives twice the incoming radiation of a flat surface, air temperature is increased by 3.6 °F, but the same site with a LAI = 5.0 would have no temperature increase. The temperature calculation is written generally as:

$$T_{site_S} = T_{ave} - T_{lap}\,((SE - BE)/1{,}000) + (RADRAT)\,(1 - SLAI/MLAI) \quad (2a)$$

$$T_{site_N} = T_{ave} - T_{lap}\,(SE - BE)/1{,}000 - 1/(RADRAT)\,(1 + SLAI/MLAI) \quad (2b)$$

where:

T_{site_S} = final calculated site temperature, °F or °C for south aspects
T_{site_N} = final calculated site temperature, °F or °C for north aspects
T_{ave} = Base station daylight average air temperature, °F or °C (from equation 1)
T_{lap} = elevational lapse rate correction, °F/1,000 ft
SE = site elevation (feet)
BE = base station elevation (feet)
RADRAT = ratio of slope radiation/flat surface radiation
SLAI = site leaf area index
MLAI = maximum leaf area index is 10

Because NWS temperatures are recorded at screen height (4.5 ft), this procedure will not estimate temperatures of bare surfaces accurately. But temperatures of evergreen canopies are approximately equal to screen height air temperatures because of the efficient turbulent mixing and vertical depth of the canopy energy-absorbing surface (Denmead and Bradley 1985; McNaughton and Jarvis 1983). Details of the air temperature subroutine are shown in the program code (appendix A).

Humidity—Daily dewpoint temperatures are recorded at primary NWS stations, which provide a convenient starting point for humidity calculation. We assume dewpoint to be constant for the daylight period (Kaufmann 1984), and have found dewpoint to be relatively constant spatially on any given day over a relatively large area. This gives us confidence in the horizontal extrapolation of the humidity measurement (fig. 13, in appendix C). Obviously, relative humidity is not constant over large areas because of temperature differences. When dewpoint data are not available, we assume that the night minimum temperature is equal to the daily dewpoint. We tested the relationship between night minimum temperature and dewpoint with two data sets (fig. 14, in appendix C). This logic deteriorates in arid environments where dewpoint is not reached regularly, yet even in dry central Montana a strong relationship exists between night minimum temperature and dewpoint.

Dewpoint, either measured or estimated from the base station minimum temperature, is then corrected using an elevational lapse rate of 1.5 °F/1,000 ft, modified slightly to account for radiation load (Finklin 1983).

Finally, the estimated dewpoint for the site is combined with the estimated air temperature to derive daylight averages of relative humidity using equations of Murray (1967). The humidity equations are given in appendix G and in the program code (appendix A).

Precipitation—In mountainous terrain, precipitation is highly variable in both timing and duration. We felt a mechanistic submodel at a daily time step was not possible within the scope of this work (Finklin 1983). As a simple alternative, we use a ratio of annual precipitation of the site to two base stations. The model will run using only one base station. Site annual precipitation is estimated from annual isohyet maps while base station annual precipitation is obtained from long-term averages for the base stations used. The site/base station ratios are multiplied by measured base station precipitation and averaged to obtain daily precipitation estimates for the study site. Equations are shown in appendix F and in the Rain subroutine in the program code (appendix A).

EXECUTING MTCLIM

Location of the Program

The program is written in FORTRAN and is currently available on the Forest Service Data General System and on floppy disks for IBM-compatible personal computers. Copies of the program can be obtained by contacting the authors.

Creating Input Files

The program requires two input files for execution and a third file for the output. The initialization file, INIT.DAT, identifies the names of the base station file and the output file and contains information about the base station(s) and the site. The second input, base station file, contains data for the selected base station(s).

Initialization File (INIT.DAT)—This file initializes the program with the information that is essential for running MTCLIM. The format set up (table 1) shows input identified by the headings. The user can identify this file as INIT.DAT or may use any name and file extension. The first two lines are for comments. Data are entered into columns 1 to 12 in *capital* letters. Columns 13 and up are reserved for comments. The first input asked for is the name of the file that contains the base station data. The file can be identified using the appropriate file designations for the machine being used. The output file name is identified in the same manner. Output from the model is put in this output file.

The remaining input values are discussed below by output and input options, base station characteristics, site characteristics, and model adjustments.

Output and Input Options—The output and input options for MTCLIM are specified in lines 5 to 11 of the initialization file (table 1). Input and output units are identified here. Also the number of days to be extrapolated and options for input data are identified here.

UNITS	This input (line 5) identifies whether the data in the base station file identified above is in English (E) units (temperature in degrees Fahrenheit and precipitation in inches) or SI (S) units (temperature in degrees Celsius and precipitation in centimeters).
DEWPOINT	This input identifies whether or not dewpoint temperatures are supplied in the base station data file. Enter a Y (yes) or N (no). If dewpoint is not supplied the program will use minimum temperatures to estimate dewpoint.
NO. PPT STATIONS	Enter 1 if there are data for only one precipitation station in the base station file, or 2 if data for two stations are used.

Table 1—Format for initialization (INIT.DAT) file used to initialize the MTCLIM program. Name of files for base station input data and the output file are identified. Base station and site characteristics are also input along with values for several model parameters

```
 1  MTCLIM INITIALIZATION DATA FILE: USE LINES 1 AND 2 FOR COMMENTS
 2  COMMENT LINE (CONT'D)
 3  MS083.IN        INPUT DATA FILE (INDICATE UNITS IN THIS SPACE)
 4  MS083.OUT       OUTPUT DATA FILE
 5  E *             ENGLISH (TEMPS:F AND PPT:INCHES ) OR SI (C & CM) UNITS. (E OR S)
 6  N               DEW POINT TEMPERATURE SUPPLIED (Y OR N)
 7  1               NUMBER OF PPT STATIONS (1 OR 2) IF 2 THEN USE 2 ISOHYETS BELOW
 8  N               USE THRESHOLD RADITATION (Y OR N)
 9  A               TOTAL OR AVERAGE RADIATION (T OR A)
10  Y               USE YEARDAY(JULIAN) IN PLACE OF MONTH & DAY (Y OR N)
11  172             NDAYS   INTEGER VARIABLE; ALL THE REST ARE REAL
12  46.9            LATITUDE
13  6000.0          SITE ELEVATION (METERS FOR SI OR FEET FOR ENGLISH)
14  3190.0          BASE ELEVATION (METERS FOR SI OR FEET FOR ENGLISH)
15  000.0           SITE ASPECT  0 to 360 degrees (0 = NORTH; 180 = SOUTH)
16  00.0            SITE SLOPE  (PERCENT)
17  1.0             SITE LAI (ALL SIDED)
18  18.0            SITE ISOHYET (PRECIPITATION)
19  12.0            BASE ISOHYET STATION 1
20  00.0            BASE ISOHYET STATION 2 (OPTIONAL) SEE NUMBER OF PPT STATIONS
21  2.00            SITE EAST HORIZION (DEGREES)
22  5.00            SITE WEST HORIZION (DEGREES)
23  0.2             SITE ALBEDO  (.2 = 20%)
24  0.65            TRANCF  (SEA LEVEL ATMOSPHERIC TRANSMISSIVITY)
25  0.45            TEMPCF  (TEMPERATURE CORRECTION FOR SINE APPROX)
26  3.5             TEMP LAPSE RATE    (DEGREES / 1000 METERS)
27  4.0             LASPE RATE FOR MAXIMUM TEMPERATURE   (DEGREES / 1000 M OR FT)
28  2.0             LAPSE RATE FOR MINIMUM TEMPERATURE   (DEGREES / 1000 M OR FT)
29  1.5             DEW LAPSE RATE   (DEGREES / 1000 M OR FT)

  *  Enter data in colums 1-12.  Letters should be in caps.
```

RADIATION THRESHOLD	If the output is wanted using the 70 W/m^2 threshold, enter Y (yes); if sunrise to sunset radiation values are wanted enter N (no).
TOTAL OR AVERAGE RADIATION	If solar radiation output (written to the output file) is desired as a daily total (kJ/m^2) enter T. If an average rate (W/m^2) is wanted enter A.
YEARDAY OR MONTH AND DAY	If input data (base station file) uses Julian day, rather than month and day, enter Y (yes); otherwise enter N (no). Setting this switch also specifies how day will be expressed in the output file.
N DAYS	Number of days that MTCLIM will make predictions for. This number can be less than the number of records in the base station input file, but *not more* or the program will abort.

Base Station Characteristics and Selection—Selection of the primary base station to use for MTCLIM is not too critical, except that the data should be of high quality. As noted previously, we used NWS stations because they are fairly well distributed and the data are readily available. Other stations, such as fire weather stations, RAWS, and other sources can be used if data are available for the desired time period. Extrapolations by MTCLIM will likely be more accurate the closer the base station is to the site. A secondary base station may be used for precipitation data. This station should also be as close to the site as possible, but in the opposite direction from the site as the first base station. More details about selection of this station are discussed in the section evaluating the precipitation estimates (page 00). Values for the following parameters are for the primary base station unless noted otherwise.

LATITUDE — This input is in degrees and tenths of degrees on line 12. Latitude is often available with the data, or can be obtained from maps.

BASE-ELEV — Elevation of the base station in feet or meters (line 14). If not part of the station documentation, it can be estimated from topographic maps.

BASE1-ISO — Long-term average annual precipitation (inches or centimeters) for the primary base station (line 19). If not part of the documentation for the station, a value can be obtained from isohyet maps prepared by the Soil Conservation Service.

BASE2-ISO — Long-term average annual precipitation (inches or centimeters) for the secondary base station (line 20). If not part of the documentation for the station, a value can be obtained from isohyet maps prepared by the Soil Conservation Service. Enter 0.0 if MTCLIM is run using only the primary station.

Site Characteristics—The site being modeled by MTCLIM can be a specific stand or other designated area, but the site characteristics should be consistent across the area. For example, major differences in elevation, slope, aspect, or Leaf Area Index (LAI) within one site would require the user to consider the area as different sites.

SITE-ELEV — Elevation in feet or meters (line 13). This is readily available from topographic maps.

SITE-ASPECT — Aspect in degrees from north (0°) can be measured either onsite or obtained from topographic maps (line 15).

SITE-SLOPE — Slope as percent and measured on the site (line 16). Slope can also be estimated from topographic maps.

SITE-LAI — LAI (Leaf Area Index) is a dimensionless value that represents square meters of leaf area per square meter of ground surface (line 17). LAI is a physiological estimate of canopy coverage. Estimates of LAI can be made from stand basal area using equations (Kaufmann and others 1982; Hungerford 1987) or using instruments (Pierce and Running 1988). Figure 2 shows a relationship between basal area and LAI for several species, which can be used to estimate LAI. This relationship is not available for other species but Douglas-fir, grand fir, and western hemlock would be similar to Engelmann spruce and subalpine fir; ponderosa pine would be similar to lodgepole, but the slope would be slightly higher.

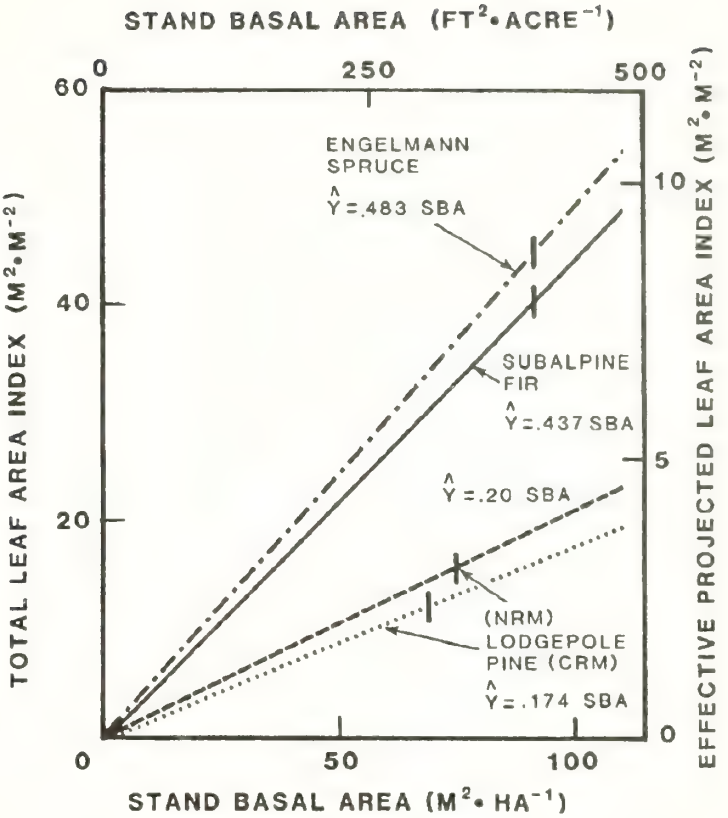

Figure 2—Effective projected and total leaf area index as a function of stand basal area for three species. This graph and the equations can be used to estimate LAI in the Central and Northern Rocky Mountains (from Kaufmann and others 1982).

SITE-ISO — Average annual precipitation isohyet (inches) for the site can be obtained from isohyet maps prepared by the Soil Conservation Service if specific data are not available (line 18).

EAST-HORZ
WEST-HORZ — These are angles to the east (line 21) and west (line 22) horizons that are used to truncate direct beam solar irradiance due to blocking by ridges or timber edges. They can be measured degrees onsite or obtained from topographic maps (see appendix E).

SALBDO — Albedo for the site represents the amount (percent) of solar radiation reflected by the surface back into the atmosphere (line 23). The value changes with the type of surface material on the site. Some typical values for different materials are given in the following tabulation (Fowler 1974; Lowry 1969; Rosenberg 1974):

Surface	Albedo *Percent*
Forest canopy	10-20
Soils	20-35
Rock	10-30
Peat	5-15
Needles and litter (dry)	6-11
Bark	20
Grass	20-25
Chips	36
Charcoal	2
Snow	80-95

Model Adjustments—The model is adjusted by changing the values for the coefficients in the initialization file (lines 24-29). These coefficients adjust clear sky transmissivity, daylight average temperature amplitude, and temperature-elevational relationships. The following discussion describes the parameters, gives starting values, and suggests values for different conditions.

TRANCF Clear sky transmissivity at sea level is needed to calculate solar radiation and adjust for cloud cover. For our tests, we assumed TRANCF to be 0.65 and increase it as elevation increases. This value is based on Gates (1980) and Bristow and Campbell (1984) and our testing of the model. It is selected from the range of possible values and is realistic for western Montana.

Turbidity of the atmosphere due to dust, pollutants, and atmospheric constituents such as ozone, oxygen, water vapor, and clouds, cause the variable attenuation of radiation by influencing transmissivity. Thus, TRANCF may be as low as 0.40 at sea level under turbid conditions and as high as 0.80 under very clear conditions at high elevations (Gates 1980). Since the model calculates transmissivity changes due to moisture and clouds, the other factors need to be accounted for. If information is available to suggest a value different from 0.65 for your area, it should be changed. Also, the value of the coefficient can be changed if the information is *not* available, but a value different from 0.65 is suspected because outputs from this model are different from observed values. This is discussed more later in the section discussing evaluation of MTCLIM.

TEMCF Daylight average coefficient is used in the equation for calculating daylight average temperature (equation 1, page 4). This coefficient adjusts the daylight average temperature above the daily mean. For the western Montana area, where this model was developed, a coefficient value of 0.45 worked well for all sites. This value is input in the initialization (INIT.DAT) file and can be changed if desired. For sites and base stations where the diurnal temperature curve more closely approximates the sine function, the value of TEMCF will be lower. Assuming the sine wave approximation, the value of TEMCF is 0.212. Measured temperature data can be used to evaluate TEMCF for a given locale if they are available. See appendix B for details.

TLAPSE Elevational lapse rate used for the daylight average temperature calculations. We used a value of 3.5 °F/1,000 ft (6.4 °C/1,000 m) for western Montana. This value is based on weather data (Finklin 1983, 1986). If data from other locations indicate a different value, TLAPSE can be changed.

MAXLAP Elevational lapse rate used for maximum temperature calculations. We used a value of 4.5 °F/1,000 ft (8.2 °C/1,000 m) for western Montana which is based on Finklin (1983, 1986). This rate seems to represent an average between mountain and canyon stations during the summer period. Lapse rates are different during the winter (Finklin 1983, 1986). If data from other locations indicate a different value, MAXLAP can be changed.

MINLAP Elevational lapse rate used for minimum temperature calculations. Information for our area suggested that lapse rates are from 1.8 to 3.3 °F/1,000 ft (3.3 to 6.0 °C/1,000 m). (Finklin 1983, 1986). Our unpublished data suggest different rates, depending on whether a site is on a mountain slope, a creek bottom, or a mountain basin. Our results indicate that a value of 0 to 2.0 °F/1,000 ft (0 to 3.8 °C/1,000 m) is appropriate, when moving from valley bottom base stations to

mountain slope sites. Lapse rates from valley bottom stations to basin, mountain meadows, or creek bottoms seem to be 8.0 to 10.0 °F/1,000 ft (14.6 to 18.2 °C/1,000 m) for a moderate increase in elevation. In September and October, an inversion takes place and minimum temperatures are 2.0 to 4.0 °F/1,000 ft (3.8 to 7.5 °C/1,000 m) *warmer* than valley bottom base stations. More in-depth discussion of these lapse rates is found later in the model evaluation section.

DEWLAP — Elevational lapse rate for dewpoint used for calculating relative humidity. Finklin (1983) reports this value as 1.5 °F/1,000 ft (2.7 °C/1,000 m) for western Montana. This is likely to change for other regions; thus it should be adjusted.

Base Station Data—This file contains meteorological data for the primary base station and precipitation data for the secondary base station, if desired. Table 2 shows the input variables and a sample of data. It is not important what columns the variables are in as long as they are in the order shown and have at least one blank column separating the variables.

MONTH	Month is entered as a numeric value from 1 to 12.
DAY	Day of the month is entered as a numeric value.
(JDAY)	Julian Day can be used instead of month and day. The method used is indicated on line 10 in the initialization file.
MAXIMUM TEMP (MAX)	This is maximum temperature (°F or °C) observed for each day at the base station. Values can be input in whole degrees.
MINIMUM TEMP (MIN)	This is minimum temperature (°F or °C) observed for each day at the base station. Values can be input in whole degrees.
DEWPOINT (DEWPT)	If dewpoint data are used, they are entered as °F or °C. Values can be input in whole degrees. If dewpoint is not used, nothing is entered and the program will read precipitation as the next variable.
PRECIPITATION BASE1	Daily precipitation for the primary base station in inches or centimeters. If there is no precipitation, enter 0.
PRECIPITATION BASE2	Daily precipitation for the secondary base station in inches or centimeters. If there is no precipitation, enter 0. If a second base station is not used, enter all 0's.

MTCLIM Output File

The program output is printed in tabular form (table 3), with values for solar radiation, temperature, humidity, and precipitation presented by month and day or Julian day. The number of days in this file are based on the number of days specified in the initialization (INIT.DAT) file. If averages for other time periods (10 days, monthly, etc.) are desired, these data can be summarized from the predicted data in this file. Statistics concerning variation can be calculated, if desired. The program prints a copy of the initialization (INIT.DAT) file before printing the output. This helps keep track of the values used for each run.

Table 2—Sample input data file for base station. Headings show the inputs needed and the units. In creating the file, headings will not be input. This sample is for only 1 month. In an actual run these data will need to cover the time period to be predicted

		Temperature			Precipitation[1]	
MO[2]	DAY[2]	MAX	MIN	DEWPT[3]	BASE1	BASE2[4]
		---°F[5]---			----*Inch*[5]----	
7	01	78	45		0	0
7	02	81	50		0.34	0
7	03	70	54		.37	0.30
7	04	73	50		.03	.30
7	05	71	51		.18	.15
7	06	77	48		.02	.06
7	07	84	47		0	0
7	08	80	56		0	0
7	09	81	49		.10	.10
7	10	73	49		0	0
7	11	83	43		0	0
7	12	75	55		.23	0
7	13	68	50		.18	.13
7	14	59	45		.09	.05
7	15	75	51		.01	.19
7	16	85	46		0	0
7	17	76	48		0	0
7	18	74	46		0	0
7	19	80	46		0	0
7	20	80	47		0	0
7	21	90	49		0	0
7	22	97	53		0	0
7	23	92	61		0	.01
7	24	87	50		0	0
7	25	88	53		0	0
7	26	87	52		0	0
7	27	89	51		0	0
7	28	92	50		0	0
7	29	87	56		0	0
7	30	92	48		0	0
7	31	89	46		.03	0

[1]Enter precipitation as inches or centimeters and specify which in initialization file.

[2]Julian day may be used instead of month and day. The method used in this file must be indicated on line 10 of the initialization file.

[3]If dewpoint is not used, nothing is entered. Precipitation will start in these columns instead.

[4]If data for a second base station are not used, zeroes must be entered or the program will abort.

[5]The units printed out will depend on whether English or SI units are specified in the initialization file.

Table 3—This is a sample of the MTCLIM output with values for the month of July. The program (as shown here) prints the initialization (INIT.DAT) file at the top to make it easy to identify the input values for each run

```
 MTCLIM OUTPUT FILE
 A LISTING OF INITIALIZATION FILE FOLLOWED BY OUTPUT:

MTCLIM INITIALIZATION DATA FILE: AMBROSE SOUTH 1983 SITE WITH
                MISSOULA NWS STATION USED FOR BASE STATION DATA
MS083.IN        INPUT DATA FILE (TEMPS IN DEGREES F)
MS083.OUT       OUTPUT DATA FILE
E               ENGLISH (TEMPS:F AND PPT:INCHES ) OR SI (C & CM) UNITS. (E OR S)
N               DEW POINT TEMPERATURE SUPPLIED (Y OR N)
1               NUMBER OF PPT STATIONS (1 OR 2) IF 2 THEN USE 2 ISOHYETS BELOW
N               USE THRESHOLD RADITATION (Y OR N)
A               TOTAL OR AVERAGE RADIATION (T OR A)
Y               USE YEARDAY(JULIAN) IN PLACE OF MONTH & DAY (Y OR N)
15              NDAYS   INTEGER VARIABLE; ALL THE REST ARE REAL
46.9            LATITUDE
6000.0          SITE ELEVATION (METERS FOR SI OR FEET FOR ENGLISH)
3190.0          BASE ELEVATION (METERS FOR SI OR FEET FOR ENGLISH)
000.0           SITE ASPECT  0 to 360 degrees (0 = NORTH; 180 = SOUTH)
00.0            SITE SLOPE  (PERCENT)
1.0             SITE LAI (ALL SIDED)
18.0            SITE ISOHYET (PRECIPITATION)
12.0            BASE ISOHYET STATION 1
00.0            BASE ISOHYET STATION 2 (OPTIONAL) SEE NUMBER OF PPT STATIONS
0.00            SITE EAST HORIZION (DEGREES)
10.0            SITE WEST HORIZION (DEGREES)
0.2             SITE ALBEDO  (.2 = 20%)
0.65            TRANCF  (SEA LEVEL ATMOSPHERIC TRANSMISSIVITY)
0.45            TEMPCF  (TEMPERATURE CORRECTION FOR SINE APPROX)
3.5             TEMP LAPSE RATE    (DEGREES / 1000 M OR FT)
4.0             LASPE RATE FOR MAXIMUM TEMPERATURE   (DEGREES / 1000 M OR FT)
2.0             LAPSE RATE FOR MINIMUM TEMPERATURE   (DEGREES / 1000 M OR FT)
1.5             DEW LAPSE RATE   (DEGREES / 1000 M OR FT)


JDAY  RADIATION  STEMP MAXT  MINT  RH   PPT
        W/M**2   F     F     F     %     INCHES
 121    448.32   50.   54.   37.   65. 0.00
 122    397.73   46.   50.   34.   67. 0.08
 123    457.38   45.   48.   34.   70. 0.00
 124    560.37   46.   54.   24.   44. 0.00
 125    345.09   48.   55.   27.   47. 1.32
 126    161.92   39.   42.   28.   70. 0.34
 127    403.16   45.   51.   27.   52. 0.21
 128    175.05   40.   43.   29.   70. 0.34
 129    135.20   29.   29.   28.   99. 0.52
 130    308.50   35.   37.   28.   80. 0.03
 131    451.60   36.   40.   23.   63. 0.00
 132    513.61   38.   43.   22.   56. 0.00
 133    582.63   44.   51.   22.   45. 0.00
 134    569.53   46.   54.   24.   44. 0.00
 135    196.51   41.   43.   32.   76. 0.76
```

DATE	This will be printed as Julian day or month and day based on entry on line 10 of the initialization (INIT.DAT) file.
SOLAR RADIATION (RADIATION)	Solar radiation (table 3) is expressed as either a daily total (in kJ/m^2) or an average rate for the day (in W/m^2), depending on user preference. This output will be expressed using the 70 W/m^2 threshold value or sunrise to sunset values for daylength.
DAY AVERAGE TEMP (STEMP)	Temperature averaged over the daylight hours (sunrise to sunset). Outputs can be in degrees C or F (based on entry on line 5 in initialization file).
MAXIMUM TEMP (MAXT)	Daily maximum temperature can be in degrees C or F (based on entry on line 5 in initialization file).
MINIMUM TEMP (MINT)	Daily minimum temperature can be in degrees C or F (based on entry on line 5 in initialization file).
HUMIDITY (RH)	Relative humidity (percent) averaged over the daylight hours (sunrise to sunset).
PRECIPITATION (PPT)	Daily total precipitation in inches or centimeters (based on entry on line 5 of initialization file).

Executing MTCLIM

General Use—Once the initialization (INIT.DAT) and Base Station files have been created as described in the previous section, MTCLIM is ready to run, (assuming the program is compiled on the machine being used). When the program is started, it will ask for the name of the initialization (INIT.DAT) file. After the file name is given, MTCLIM will execute and put the output, as in table 3, in the file designated in the initialization (INIT.DAT) file.

The source code and the executable program can be mailed on the Forest Service Data General System to any system user. The source code, executable files, the initialization (INIT.DAT) file, and some help files are available on 5 1/4-inch floppy discs for IBM and IBM compatible PC's.

EVALUATION OF MTCLIM

Procedures

To test the accuracy of MTCLIM calculations, observed data from several sites in western Montana were selected (Hungerford and Babbitt 1987; Hungerford and Schlieter 1984; Running and others 1987). These data, which were not used to develop the equations in MTCLIM, were summarized to daylight average, maximum and minimum air temperatures, and daily solar radiation for each of the sites. The observed daily values were compared to daily MTCLIM predictions for May 1 to October 31, using simple linear regression analysis of predicted data versus observed data. Table 4 shows the characteristics of nine sites and the base stations used in the analyses. These sites represent a variety of elevations and slope positions. Specific sites used to generate model output are shown in table 5. Details for the precipitation tests are given later.

Solar Radiation

Because solar radiation data are not available for all sites, our evaluations were limited to the Ambrose S, Ninemile S, and Coram 12 (table 5) sites.

Results for the linear regression analyses of observed and predicted daily radiation are shown in table 6 for the three sites. The slope for all three sites (0.65 to 0.78) is less than 1.0 and the intercepts for all sites are greater than zero. The r^2 values of 0.50 to 0.55 are not as good as desired, but are reasonable considering the

Table 4—General characteristics of study sites and base stations

Site	Aspect	Slope	Elevation	Distance to base station
	Degrees	*Percent*	*Feet*	*Miles*
Lubrecht (clearcut)	0	0	4,000	32
Coram 14 (uncut)	112	60	4,400	15
Coram 12 (clearcut)	112	50	4,350	15
Coram 33 (clearcut)	270	5	3,950	15
Ambrose N	350	40	6,000	32
Ambrose S	195	50	6,000	32
Ninemile N	330	40	5,600	25
Ninemile S	170	50	5,600	25
Schwartz N	40	40	5,000	19
Kalispell Base	0	0	2,965	0
Missoula Base	0	0	3,190	0

Table 5—Sources of data used for evaluation of each model output

Site	Radiation	Temperature			Humidity
		Day	Maximum	Minimum	
Lubrecht		x	x	x	
Coram 14		x	x		
Coram 12	x	x	x	x	
Coram 33		x	x	x	
Ambrose N		x		x	x
Ambrose S	x	x	x		x
Ninemile N		x			x
Ninemile S	x	x		x	x
Schwartz N		x			x

Table 6—Predicted vs. observed solar radiation comparisons for three sites using linear regression analysis

Site	Intercept	Slope	r^2	SEE[1]	*n*
Ambrose S[2]	102	0.78	0.55	102	174
Ambrose S[2]	0	.98	.50	106	174
Ninemile S[2]	143	.65	.50	104	146
Ninemile S[2]	0	.93	.40	114	146
Coram 12[3]	5.6	.74	.50	4.4	184
Coram 12[3]	0	1.07	.38	4.8	184

[1]Standard error of the estimate.
[2]W/m^2.
[3]In mJ/m^2.

variation in cloud cover between the base stations and sites. Figure 3 shows a plot of predicted vs. observed daily radiation for Ambrose S compared to the 1:1 line. It shows that the model overpredicts for cloudy days and underpredicts for clear days. When the intercepts for the regression are forced through the origin, the slopes are much closer to 1.0 (table 6). In this constrained regression, the standard error of the estimate increases slightly and r^2 drops (table 6). Although the statistics are not quite as good for the constrained regression, having the intercept through the origin is much more realistic. This analysis shows that we slightly underestimated radiation at Ambrose S (fig. 3) and Ninemile S, while the model overestimated radiation

at Coram 12. Figure 4 shows the daily comparison of predicted and observed solar radiation for the Ninemile site. Only 2 out of every 3 days are plotted. The closeness of the lines indicate that predicted and observed solar radiation values are close for most days.

Evaluation of outlying values and residuals in figure 3 indicated that most overpredictions were the result of cloudier conditions at the mountain site than at the base station. We frequently observed that when it was partly cloudy at valley locations, clouds were stacked up against the mountains; thus, predictions using base station data in valley bottoms will overpredict at mountainous sites. Analysis of underpredictions revealed that these occurred on days when weather was changing; thus, the temperature amplitude was small. As a result, the model simulated cloudy skies when skies were actually clear; thus, the predicted radiation is low (see appendix A for details of calculation).

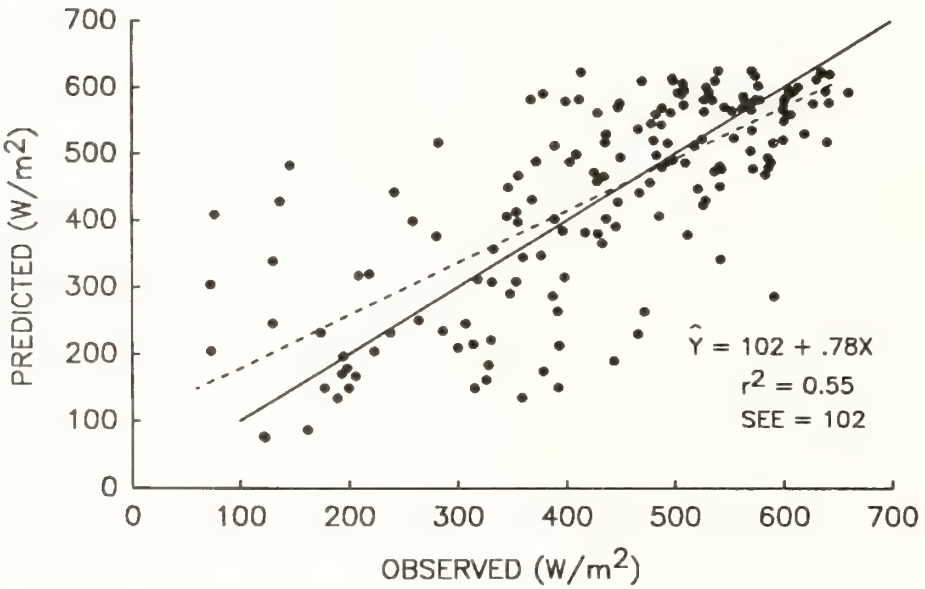

Figure 3—Regression of incoming solar radiation predicted by MTCLIM vs. actual radiation observed at Ambrose S. Broken line is the regression line and the solid line is the 1:1 line (intercept = 0; slope = 1.0).

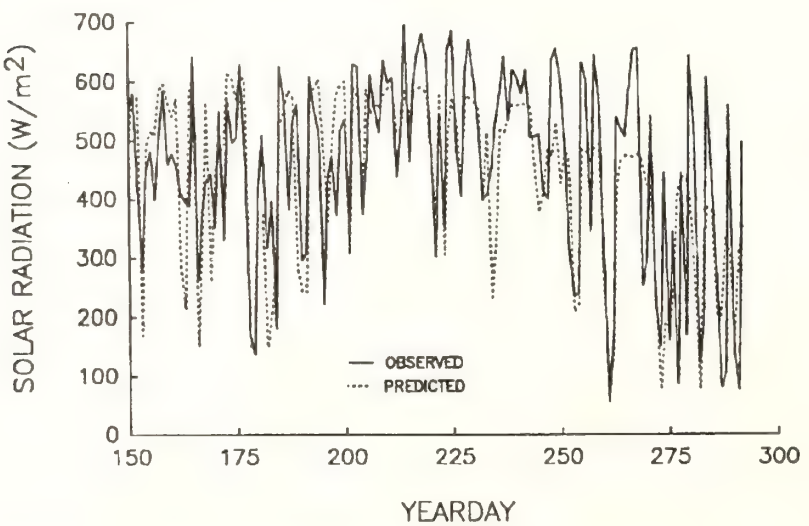

Figure 4—Comparison of observed (solid line) and MTCLIM estimated (broken line) daily solar radiation at Ninemile S.

Predictions of radiation from this model using data from valley bottom stations are reasonably accurate when averaged over a season, but daily predicted values can be quite different from observed values. Predictions can be improved significantly if base station input data are used from a mountain location or a site very close to the site being predicted (Bristow and Campbell 1984). This would reduce the errors introduced by differences in cloud cover from valley bottom to mountain sites. Underprediction errors resulting from small temperature amplitudes that predict cloud cover when it is actually clear will be created by MTCLIM regardless of choice of base station. Fortunately this situation occurs infrequently.

Temperature

Evaluations of the temperature predictions are also made using linear regression analysis of predicted and observed temperatures. Analyses of day average and maximum and minimum temperature will be discussed separately.

Daylight Average Temperature—Results of the predicted vs. observed regressions are given in table 7 for day average temperature on all nine sites. Overall, accuracy is about 4 °F, with intercepts from 0.5 to 2.3, slopes from 0.83 to 1.03, and r^2 ranging from 0.87 to 0.93. A typical plot of predicted vs. observed points about the 1:1 line is shown in figure 5. A small but consistent bias of overestimating low temperatures and underestimating higher temperatures is evident in these statistics, and was caused by the lapse rate chosen (3.5). But the lapse rate that was chosen appears to be the best compromise for our study area. Other lapse rates would cause greater errors at the higher or lower temperatures. Figure 6 shows a comparison of observed and predicted daylight average temperatures for Ninemile S. Only 2 out of every 3 days is plotted. The closeness of the lines indicate that predicted and observed temperature values are close for most days. Standard errors of the estimate (table 7) for the predicted and observed regressions range from 1.6 to 2.1 °C.

Table 7—Predicted vs. observed daylight average temperature comparisons for nine sites using linear regression analysis. A lapse rate of 3.5 °F/1,000 feet was used

Location	Year	Intercept	Slope	r^2	SEE[1]	n
		°C			°C	
Lubrecht	1980	2.3	0.89	0.92	1.6	131
Coram 14	1976	1.5	.98	.89	1.6	160
Coram 33	1976	1.6	1.03	.88	1.9	174
Coram 12	1976	1.5	.93	.87	1.8	163
Ambrose N	1983	.5	.89	.89	2.1	174
Ambrose S	1983	1.1	.91	.89	2.1	174
Ninemile N	1983	1.7	.92	.89	2.0	146
Ninemile S	1983	1.0	.97	.90	2.0	146
Schwartz N	1983	.8	.83	.93	1.6	172

[1]Standard error of the estimate.

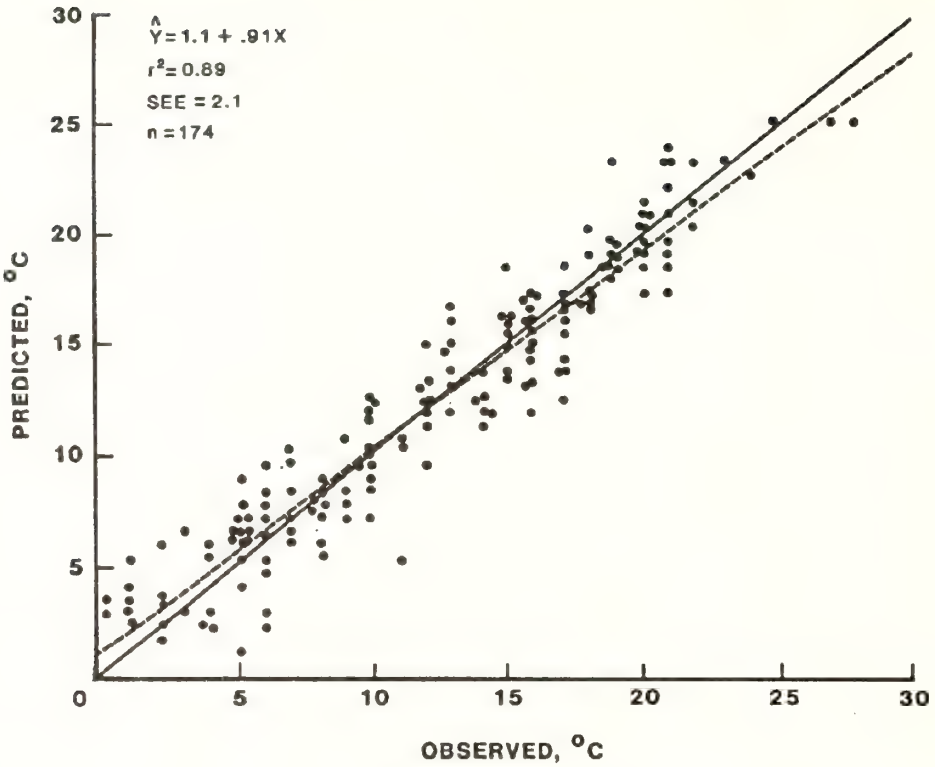

Figure 5—Regression of daylight average temperature predicted by MTCLIM on observed daylight average temperature at Ambrose S. Broken line is the regression line and the solid line is the 1:1 line (intercept = 0; slope = 1.0).

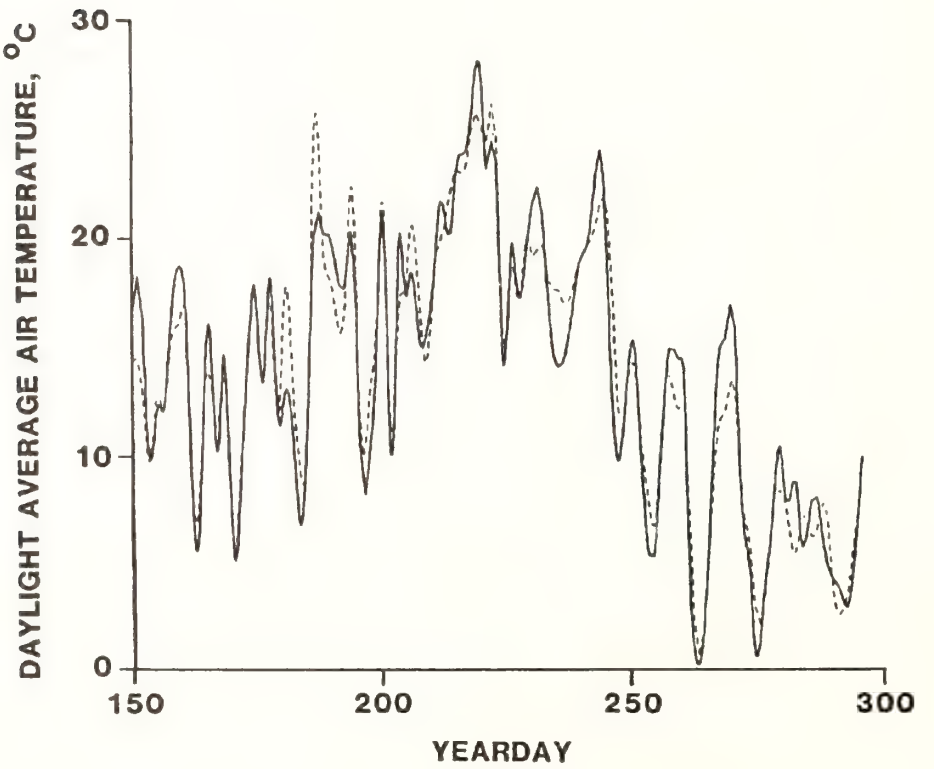

Figure 6—Comparison of observed (solid line) and MTCLIM estimated (broken line) daily daylight average temperature at Ninemile S.

Maximum Temperature—Results of the predicted vs. observed regressions for maximum temperature are given in table 8 for five sites. Overall, accuracy is about 4 °F, with intercepts from –0.69 to 2.6, slopes from 0.91 to 1.03, and r^2 ranging from 0.86 to 0.94. A typical plot of predicted vs. observed points about the 1:1 line is shown in figure 7. A small but consistent bias of overestimating low temperatures and underestimating higher temperatures is also evident in these statistics. As with the daylight average temperatures, this is caused by the lapse rate chosen (4.5). In some situations a lapse rate of up to 7.0 °F/1,000 ft may be appropriate. The lapse rate of 4.5 °F/1,000 ft, however, seems to be the best compromise for our study area in general. Figure 8 shows a comparison of observed and predicted maximum temperatures. Only 1 out of every 2 days is plotted. The closeness of the lines indicate that predicted and observed temperature values are close for most days. Standard errors of the estimate (table 8) for the regressions are 1.6 to 2.4.

Table 8—Predicted vs. observed maximum temperature comparisons for five sites using linear regression analysis

Location	Year	MAXLAP	Intercept	Slope	r^2	SEE[1]	*n*
		°F/1,000 ft	*°C*			*°C*	
Lubrecht	1980	4.5	0.56	0.94	0.94	1.6	131
Coram 33	1976	4.5	2.6	.92	.89	2.1	175
Coram 12	1976	4.5	2.1	.91	.86	2.3	172
Coram 14	1976	4.5	2.0	1.03	.92	1.7	173
Ambrose S	1983	4.5	–.69	.96	.89	2.4	174

[1]Standard error of the estimate.

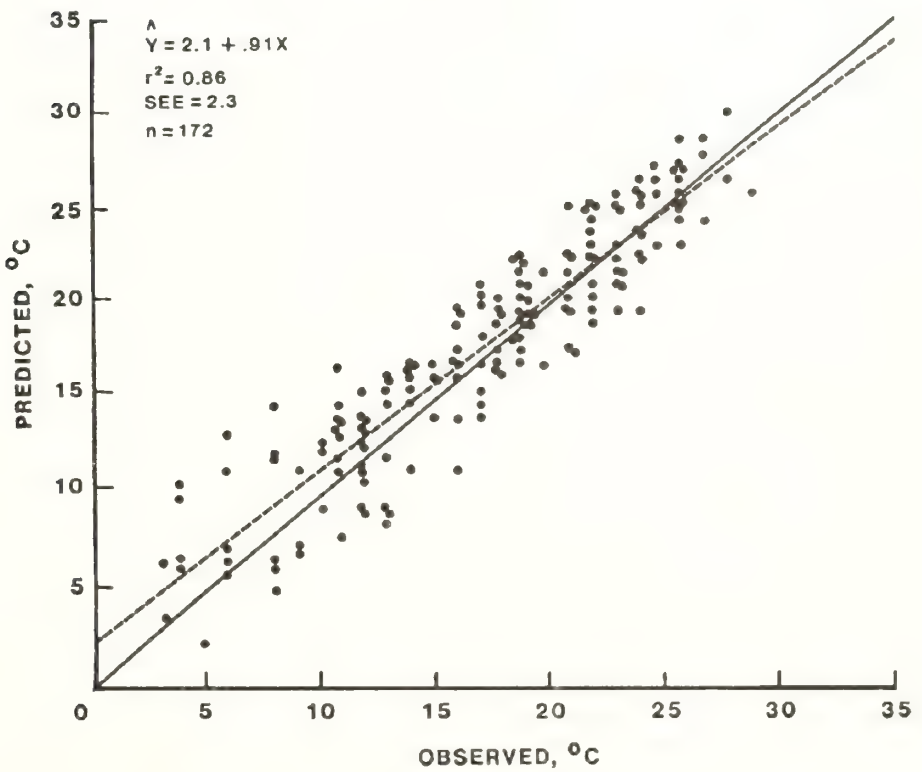

Figure 7—Regression of maximum temperature predicted by MTCLIM on observed maximum temperature at Coram 12. Broken line is the regression line and the solid line is the 1:1 line (intercept = 0; slope = 1.0).

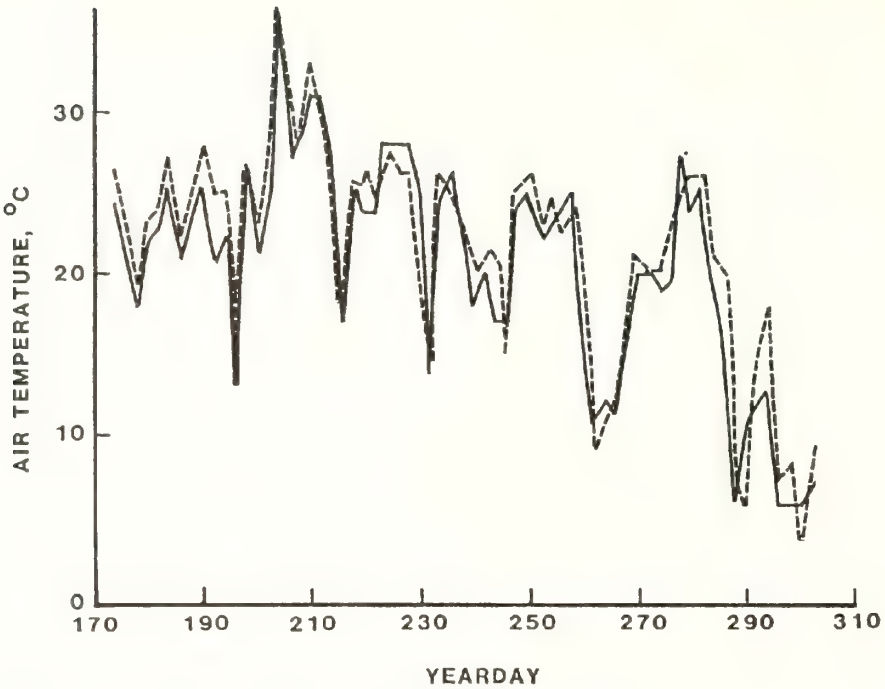

Figure 8—Comparison of observed (broken line) and MTCLIM estimated (solid line) daily maximum temperature at Lubrecht. Every other day is plotted.

Minimum Temperature—Due to the effect of frost pockets, cold air drainage, and temperature inversions, prediction of minimum temperatures was difficult. Information for our area (Finklin 1983) suggested that the lapse rate for minimum temperatures is between 1.8 and 3.3 °F/1,000 ft; therefore we chose 2.0 for our initial analysis. It became apparent right away that the accuracy of our MTCLIM minimum temperature predictions varied from less than 3 to 6 °F depending on site (table 9). The lapse rate of 2.0 °F/1,000 ft was not high enough for Lubrecht and Coram 33, which are basin or creek bottom locations that trap cold air. In some cases, the lapse rate was too high for slope sites. Comparison of the predicted and observed data also revealed that lapse rates sometimes reverse after September 1. These three situations will be discussed separately.

MTCLIM predictions at a basin location (Lubrecht) and a creek bottom station (Coram 33) were quite close to observed temperatures when a lapse rate of 10 °F/1,000 ft was used (table 9). At Lubrecht the intercept is close to zero and the slope is nearly 1.0 and $r^2 = 0.91$. At Coram 33 the r^2 is 0.70, with the intercept at –1.1 and the slope at 0.98. These statistics suggest that the lapse rate is a little high at Coram 33; it may be closer to 8.0 °F/1,000 ft. Because both of these stations are only 1,000 feet in elevation above the valley bottom base stations, a lapse rate of 10 °F/1,000 ft may predict temperatures lower than observed at locations with greater elevation differences relative to the base station. In the event that data from a slope base station are input to MTCLIM to predict minimum temperatures in a creek bottom or basin location, the lapse rate of 10 °F/1,000 ft is appropriate.

MTCLIM predictions on mountain slopes using lapse rates of 0 to 2.0 °F/1,000 ft are reasonably close to observed temperatures. Results of regressions from Coram 12, Ambrose N, and Ninemile S (table 9) show that the predictions using a lapse of zero give the best compromise considering predictions over the whole range of temperatures (fig. 9). The r^2 values 0.56 to 0.75 show that considerable daily variation exists between predicted and observed values. The slope of these relationships is not as close to 1.0 as we would like (except for Ninemile S at 0.97). For our area

Table 9—Predicted vs. observed minimum temperature comparisons for five sites using linear regression analysis. Two lapse rates are analyzed for each site

Location	Year	MINLAP	Intercept	Slope	r^2	SEE[1]	n
		°F/1,000 ft	*°C*			*°C*	
Lubrecht	1980	10.0	0.10	1.05	0.91	1.5	131
		2.0	3.70	1.05	.91	1.5	131
Coram 33	1976	10.0	−1.10	.98	.70	2.1	116
		2.0	3.28	.98	.70	2.1	116
Coram 12	1976	2.0	.76	.76	.56	2.8	118
		0	2.29	.76	.56	2.8	118
Ambrose N	1983	2.0	−.39	.77	.61	3.3	174
		0	2.70	.77	.61	3.3	174
Ninemile S	1983	2.0	−1.50	.97	.75	2.7	145
		0	.95	.97	.75	2.7	145

[1]Standard error of the estimate.

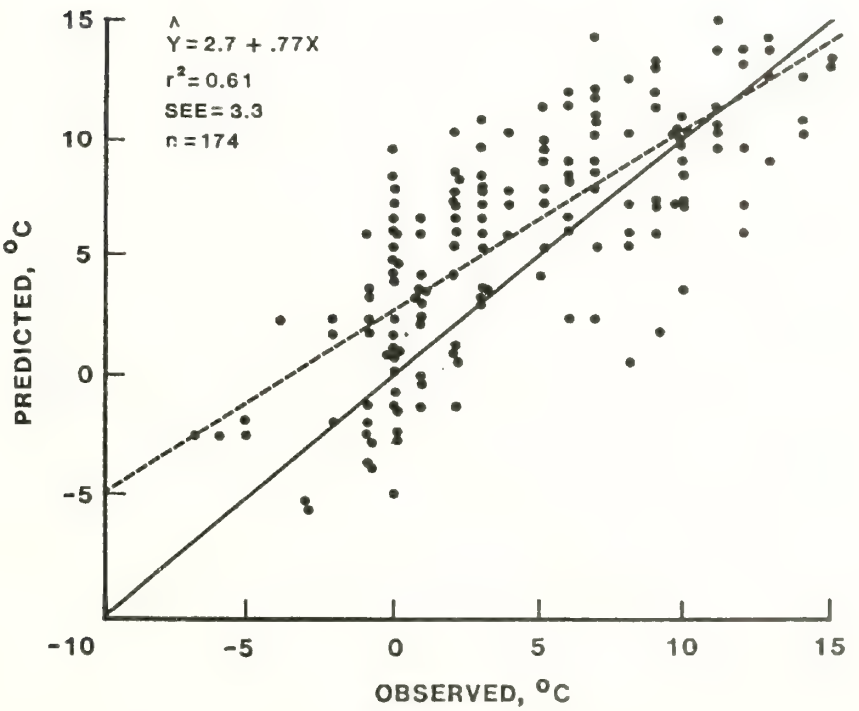

Figure 9—Regression of minimum temperature predicted by MTCLIM on observed minimum temperature at Ambrose N. Broken line is the regression line and the solid line is the 1:1 line (intercept = 0; slope = 1.0).

these results suggest that a lapse rate between 0 and 2.0 °F/1,000 ft applied to valley bottom base stations will be adequate for predicting minimum temperatures on slope sites from May 1 to September 1.

The analysis of predicted and observed regressions also indicates that minimum temperature on slopes in September and October are often warmer than at valley bottom base stations. Our data indicate an inversion of +2.0 to +4.0 °F. This temperature inversion period was not accounted for in our analysis (we used the whole period from May 1 to October 31), therefore the lapse rates for minimum temperature (MINLAP) include the inversion situations. More accurate predictions would likely result if different lapse rates were input for September and October.

Humidity

Evaluations of humidity predictions are also made using linear regression analysis of predicted and observed humidity. Results of predicted vs. observed regressions are given in table 10 for three locations. Accuracy of predictions is about 11 percent with regression intercepts from 19.7 to 23.9, slopes from 0.50 to 0.59, and r^2 from 0.43 to 0.60. Figure 10 shows that humidity is overestimated at low humidity and underestimated at high humidity, which is also indicated by the intercepts being greater than zero and the slopes less than 1.0. This pattern is partly a consequence of the tendency of the model to underpredict warmer air temperatures, when humidity would be lowest, therefore, MTCLIM overestimates lower humidities. Overpredicted cool temperatures conversely cause underpredicted high humidities. Thus, errors in temperature predictions influence the humidity predictions. Response characteristics of different humidity sensors can also contribute to differences. Figure 11 shows a daily comparison of predicted and observed relative humidity. Only 2 out of every 3 days is plotted.

Table 10—Predicted vs. observed relative humidity for three sites using linear regression analysis

Location	Intercept	Slope	r^2	SEE[1]	n
Ambrose N	19.7	0.59	0.59	9.6	174
Ninemile S	21.4	.50	.43	10.9	176
Schwartz N	23.9	.55	.60	9.2	176

[1]Standard error of the estimate.

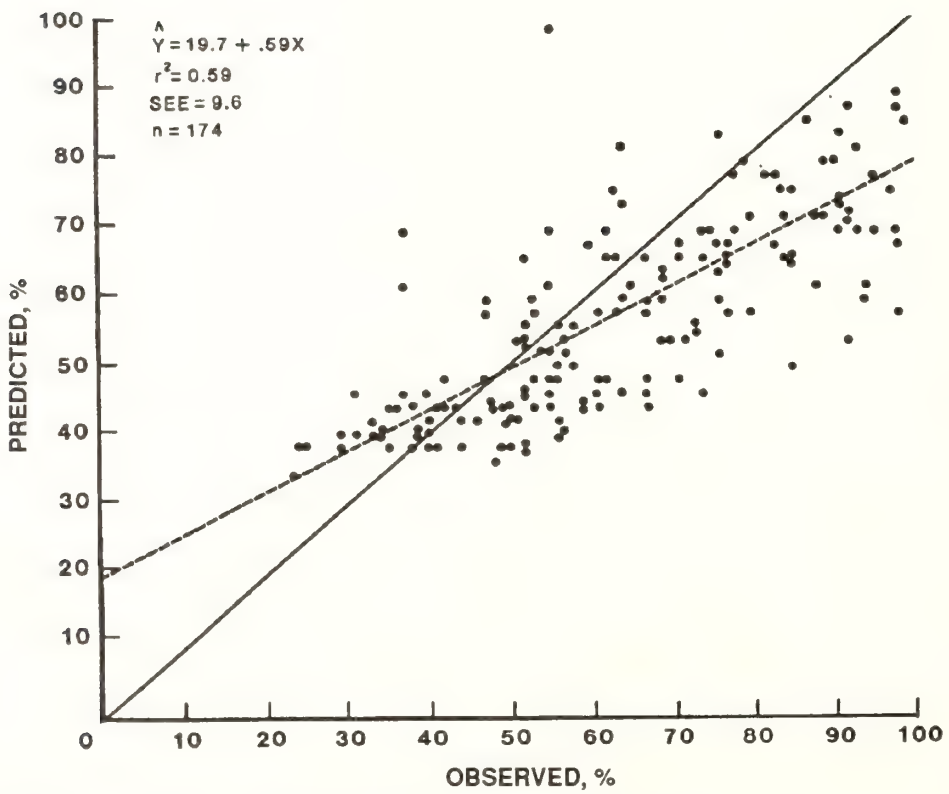

Figure 10—Regression of relative humidity predicted by MTCLIM on observed relative humidity at Ambrose N. Broken line is the regression line and the solid line is the 1:1 line (intercept = 0; slope = 1.0).

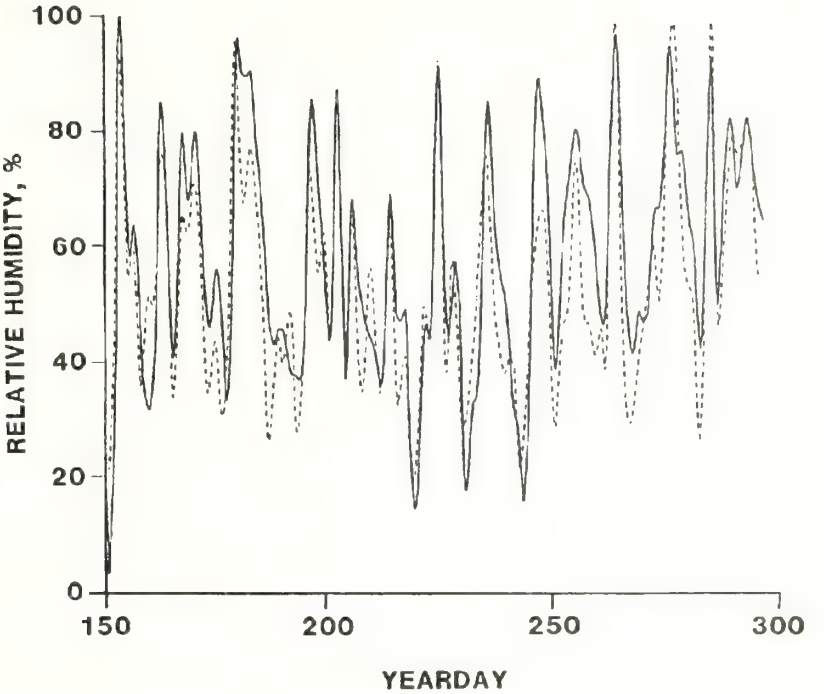

Figure 11—Comparison of observed (solid line) and MTCLIM estimated (broken line) daily relative humidity at Ninemile S.

Precipitation

Because precipitation data were not available for all nine sites, we chose five sites in mountainous areas that have published precipitation data. Observed data from these five stations (table 11) were compared with daily MTCLIM precipitation predictions using linear regression analysis. Characteristics of the five sites and the base stations used for them are shown in table 11. Five to 6 years of observations were used for the May through October period.

Results of the predicted versus observed regressions are given in table 12 using one and two base stations. Predictions are accurate to within 0.15 inches when two base stations are used, with r^2 values from 0.47 to 0.69. The intercepts for these regressions were close to 0 (0.01 to 0.03) and the slopes ranged from 0.65 to 1.01, which are reasonably close to 1.0. Standard errors of estimates ranged from 0.11 to 0.23. If only one base station is used, r^2 drops considerably (0.23 to 0.57) and standard error of the estimate increases (0.17 to 0.32). Intercepts and slopes are not much different using one or two base stations.

When a third and fourth base station were added, the amount of variation explained (r^2) and standard error of the estimate improved only slightly. The improvement in prediction over two base stations was not enough to justify the inclusion of data from additional base stations. For some of the wetter sites in the mountainous Northern Rocky Mountain area, Finklin (1987) noted that differences in precipitation compared to drier valley bottom sites are greater during the winter months than during the growing season. The consequence of this seasonal difference in pattern is that MTCLIM overestimates precipitation during the May through October period when the annual ratio of site to base precipitation is used. Finklin (1987) found that using a May through October ratio between site and base station significantly improves results (table 12). Using the May through October ratio and two base stations reduced the average percent error from +16 percent to –4 percent, reduced the standard error of the estimate, but did not change r^2. Although predictions are improved using the May through October ratio for the northern Rocky Mountains, we continue to use the annual ratio to make MTCLIM more generally applicable. We are not sure if using the May through October ratio would improve results for other regions.

Table 11—Characteristics of locations and base stations used for evaluating the precipitation subroutine

Site	Elevation	30-year average annual precipitation	Distance and direction to site
	Feet	*Inches*	
Garnet, MT	6,060	26.3	
Missoula, MT (base 1)	3,190	13.3	36 mi E
Seeley Lake, MT (base 2)	4,100	22.1	28 mi SSE
Bozeman 12 NE, MT	5,950	34.8	
Belgrade, MT (base 1)	4,451	13.8	
Bozeman, MT—MSU (base 2)	4,856	18.6	
Summit, MT		40.0	
Kalispell, MT (base 1)	2,965	15.9	40 mi E
East Glacier, MT (base 2)	4,806	30.5	12 mi SW
Deception Creek, ID	3,060	55.8	
Coeur d'Alene, ID (base 1)	2,158	25.8	14 mi ENE
Kellogg, ID (base 2)	2,305	30.4	21 mi NW
Pierce, ID	3,185	43.6	
Orofino, ID (base 1)	1,027	25.4	21 mi E
Elk River, ID (base 2)	2,918	38.5	27 mi SE

Table 12—Predicted vs. observed precipitation comparisons for five sites using linear regression analysis. Results are given using 1 and 2 base stations, the annual and May through October ratios of precipitation between site and base stations

	Annual ratio				May–October ratio			
Location	Intercept	Slope	r^2	SEE	Intercept	Slope	r^2	SEE
Garnet								
1 Base	0.03	0.84	0.30	0.22	0.03	0.70	0.30	0.19
2 Base	.02	.80	.47	.15	.02	.77	.49	.14
Bozeman I2NE								
1 Base	.02	1.04	.35	.32	.02	.72	.35	.22
2 Base	.02	1.01	.50	.23	.02	.72	.51	.16
Summit								
1 Base	.05	.73	.23	.27	.03	.49	.23	.18
2 Base	.03	.84	.54	.16	.02	.65	.59	.11
Deception Creek								
1 Base	.03	.94	.57	.22	.03	.78	.57	.18
2 Base	.03	.89	.68	.17	.03	.73	.68	.14
Pierce								
1 Base	.01	.94	.57	.18	.01	.89	.57	.17
2 Base	.01	.83	.68	.12	.01	.84	.69	.12

Results of these analyses indicate that selection of base stations for precipitation is important. Correlations between individual base stations and the five site stations varied considerably. In general, correlations decreased as distance from the site to the base station increased. When two base stations are used, they should be selected to be in opposite directions from the site, if possible. Base stations should also be in the same prevailing weather path as the site location. If available data from airport stations are not suitable, data from stations in the monthly climatological data state summaries could be useful.

USING MTCLIM AS A MANAGEMENT TOOL

In general, MTCLIM has utility in situations where weather data are needed but observations are unavailable. MTCLIM output can be used as input to existing models of ecosystems, growth and yield, insect and disease behavior, regeneration, etc., or for studying the causes of some past event where weather conditions need to be reconstructed. It can also be useful to use MTCLIM to evaluate differences between sites with distinct topographic differences, and develop management alternatives based on climatic regimes.

The following categories give some suggestions of broad uses, but are by no means exhaustive. One should always remember that output accuracy for MTCLIM predictions must be compatible with the requirements of input accuracy of data for the desired use.

Ecosystem Modeling Applications

It is generally accepted that the structure and composition of western forests are influenced by climatic and related topographic factors (Daubenmire 1956). Because of this relationship, ecological modeling applications require meteorological data as inputs. Many ecological issues focus on watersheds, to regional and even global scales. Photosynthesis (PSN), evapotranspiration (ET), decomposition, and nutrient cycling are the focus of considerable modeling efforts. In many of these applications the absence of meteorological data has hindered model application, particularly in mountainous terrain where meteorological conditions are highly variable.

Answers to questions about global climate change (Manabe and Wetherald 1980) and global vegetation dynamics (Justice and others 1985) may be enhanced by the use of meteorological data aggregated from smaller areas that are topographically detailed. At local scales, topographic variability of PSN and ET are being studied (Hasler 1982; Segal and others 1985). In an earlier paper (Running and others 1987), MTCLIM output was found to be adequate for modeling of seasonal forest ET and PSN. Values of ET and PSN calculated by MTCLIM output were within 10 percent of ET and PSN values derived from site-measured data.

A well-known ecological process model (JABOWA) of plant succession (Botkin and others 1972) uses climate variables as inputs. This model has been used to study ecological processes and to predict tree growth and rates of succession following disturbance (Botkin 1981). Keane and others (1989) have adapted a version (FIRESUM) of the SILVA process model (Kercher and Axelrod 1981, 1984) for use in the Northern Rocky Mountains. MTCLIM could be used effectively to provide input data for FIRESUM to study succession following fire. As more of these types of simulation models and "expert systems" are made available, the potential applications for the type of meteorological data produced by MTCLIM will increase.

Silviculture

Recent research on potential forest productivity or biophysical site quality (Giles and others 1985; Lee and Sypolt 1974; Running 1984b; Tajchman 1984) use site microclimate in various ways. Some more mechanistic process simulators of growth and yield also utilize inputs of meteorological data (Reed 1980). Outputs of MTCLIM may be adapted as inputs to these types of models for locations without measured weather data. If we assume that PSN production is related to long-term productivity, then linkages of MTCLIM outputs with models such as

DAYTRANS/PSN (Running 1984a, 1984b) give us a way to evaluate relative productivity of sites. Running (1984b) used a computer simulation for different environments to evaluate the effects of microclimate on productivity. Running and others (1987) found that small differences in weather made significant differences in PSN. These PSN differences were often related to aspect. Tesch (1981) found significant differences in productivity between north and south slopes. The ability exists to evaluate site response and alternative silvicultural prescriptions by using MTCLIM linked to growth simulation models such as FIRESUM (Keane and others 1987) and DAYTRANS/PSN (Running 1984b).

Meteorological parameters such as temperature, solar radiation, humidity, and precipitation are typically very important in the mountainous west for evaluating regeneration potential. Values for these variables from MTCLIM can be helpful to managers in selecting species for planting, evaluating site regeneration potential, selection of cutting and regeneration methods, and identifying problem sites.

Habitat types (Pfister and others 1977) are used to identify units of land that are similar, based on the assumption that the vegetation integrates the variation in environmental conditions. Typical weather stations are identified in the habitat classifications, but, with most stations located in valley bottoms, representative data are lacking for most habitat types. The MTCLIM model could be used to study weather variations within a habitat type or between habitat types by simulating data for a number of locations representative of the desired types. Understanding some of this variability may be useful in developing silvicultural prescriptions.

The potential for regeneration success could be evaluated using MTCLIM. Runs of the model for sites with regeneration successes could be compared with runs for sites with failures, to identify critical parameters. Critical differences in heat stress, frost, moisture stress, and radiation loads may be identified. Upon identification of critical factors, mitigation methods should be identifiable. MTCLIM may be useful for evaluating regeneration potential of sites and aiding in formulation of silvicultural prescriptions.

Fire

Weather data are very important for evaluating hazard potential, determining fire behavior, and writing prescriptions for controlled burns. The importance of weather data is evidenced by the development of NFDRS (Furman and Brink 1975), and the BEHAVE model (Andrews 1986). Many recent advances in meteorological tools and models (Fox and others 1985) aid the manager in obtaining inputs to do a better job of fire planning and management. While measurement systems through NFDRS and RAWS stations (Warren and Vance 1981) supply managers with much-needed data, the expense and logistics do not allow data measurement at all locations. We believe that MTCLIM outputs can be used to fill in the "holes" in actual weather data by extrapolating data from locations where measurements are available. Some of the subroutines in MTCLIM, such as radiation and temperature, may also be useful for calculating duff moisture for input into BEHAVE. The MTCLIM model should complement the already existing methods of data collection and the fire models available to managers, particularly in regions of complex topography.

Hydrology

MTCLIM extrapolations of weather data should be very useful for evaluating precipitation and ET potential for sites without measured weather data. Evaluations of MTCLIM output for ET calculations (Running and others 1987) indicate good results. Linkages of MTCLIM to ecosystem models described earlier for evaluating vegetation development should also help in assessing treatment-related effects on site water balance. MTCLIM outputs of solar radiation and temperature should also be useful for evaluating site and treatment differences in snowmelt.

Insects and Disease

Weather and microclimate differences are often related to insect activity (Amman 1978). MTCLIM outputs should be helpful in assessing site-specific insect activity and linking to available insect models. Disease activity is also directly related to weather and microclimate differences (McDonald and others 1987a, 1987b; Waggoner 1975); thus MTCLIM output could be valuable in assessing epidemiology of a variety of forest diseases. There is some indication that climatic stress (moisture and temperature) is important to pathogenicity of root rot caused by *Armillaria* spp. in the Northern Rocky Mountains (McDonald and others 1987b). MTCLIM may be useful in helping to understand the site-disease relationships.

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APPENDIX A: LISTING OF MTCLIM PROGRAM IN FORTRAN CODE

```
      PROGRAM MTCLIM
C  VERSION 1.0
C  6-1-89
C  THIS PROGRAM PREDICTS MICROCLIMATE CONDITIONS FOR ANY SITE
c  ON MOUNTAINOUS TERRAIN GIVEN BASE STATION METEOROLOGICAL DATA,
c  SITE AND BASE STATION CHARACTERISTICS. -RRN
C
C  ORIGINAL CODE WRITTEN BY R.R.NEMANI
C  REWRITTEN BY J.C.COUGHLAN ON 4-1-89, 6-1-89
C  MICROSOFT FORTRAN VERSION 4.1 IN STANDARD, TRANSPORTABLE FORTRAN

C  IF MTCLIM RUNS SLOW, TOO SLOW, THEN SEE SUBROUTINE RAD FOR
C  SUGGESTIONS ON OPTIMIZING THE MODEL FOR SPEED.  IT CAN BE OPTIMIZED
C  TO RUN IN HALF THE TIME IT NOW TAKES WITH A FEW CHANGES TO 1 DO
C  LOOP.  SEE SUBROUTINE RAD.  -JCC

C MTCLIM FILES/VARIABLES
C  'IFILE':FILE CONTAINING BASE AND SITE DESCRIPTIONS - SEE 'README.DOC'
C          CODE BELOW DESCRIBES SOME OF THE FILES FORMAT.
C   BFILE: INPUT- BASE STATION CLIMATE DATA
C          FILE STRUCTURE: 1 LINE PER RECORD IN FREE FORMAT
C          THE ORDER OF VARIABLES IS FOUND IN SUBROUTINE BREAD.
C   SFILE: OUTPUT- SIMULATED SITE CLIMATE FILE
C          WRITTEN IN FORMATTED OUTPUT AT END OF PROGRAM MTCLIM
C   INFILE: INTEGER FILE UNIT NUMBER CONNECTED TO BFILE
C
C SITE VARIABLES:
C   SLAT :  SITE LATITUDE
C   SELEV : SITE ELEVATION IN METERS
C   SASPCT: SITE ASPECT DEGREES
C   SSLOPE: SITE SLOPE  %
C   SLAI:   SITE LEAF AREA INDEX (ALL SIDES)
C   SISOH:  SITE ISOHYET
C   SALBDO: SITE ALBEDO %
C   SEHORZ: EAST-HORIZON
C   SWHORZ: WEST HORIZON
C   SFILE:  FILE NAME FOR OUTPUT OF MICROCLIMATE OF THE SITE
C
C BASE VARIABLES:
C   BELEV: BASE ELEVATION IN METERS
C   BISOH: BASE ISOHYET
C   BMAX:  BASE MAX TEMPERATURE, CELSIUS
C   BMIN:  BASE MIN TEMPERATURE, CELSIUS
C   BPPT:  BASE PRECIPITATION OF STATION(S), 1 OR 2 ARE SUPPORTED
C   BFILE: NAME OF THE FILE CONTAINING BASE STATION MET DATA
C
C PARAMETERS:
C   TLAPSE: LAPSE RATE FOR AIR TEMPERATURE
C   DLAPSE: LAPSE RATE FOR DEW POINT TEMPERATURE
C   MAXLAP: LAPSE RATE FOR MAX TEMPERATURE
C   MINLAP: LAPSE RATE FOR MIN TEMPERATURE
C   NDAYS:  # OF DAYS TO BE SIMULATED
C   MLAI:   MAXIMUM LEAF AREA INDEX, ASSUMED TO BE 10
C
C OUTPUT VARIABLES:
C   SRAD : SITE INCIDENT RADIATION
C   STEMP: DAYLIGHT AVERAGE AIR TEMPERATURE FOR THE SITE
C   SMIN:  NIGHT MINIMUM TEMPERATURE FOR THE SITE
C   SMAX:  MAXIMUM TEMPERATURE FOR THE SITE
C   SHUMD: DAYLIGHT AVERAGE RELATIVE HUMIDITY FOR THE SITE
```

```
C   SPPT:  PRECIPITATION AT THE SITE, CM

      REAL BMAX,BMIN,BDEW,SELEV,SLAT,SASPCT,SSLOPE
      REAL BISOH(2),BPPT(2),TRAN(365)
      REAL SISOH,SEHORZ,SWHORZ,SLAI,MLAI,SALBDO
      REAL SARAD,FARAD,TLAPSE,DLAPSE,SRAD,FRAD,MAXLAP,MINLAP
      REAL BELEV, TRANCF,TEMPCF,SMIN,SMAX,SHUMD,SPPT,STEMP
      REAL X, C2F, F2C, F2M
      CHARACTER *1 ANS0,ANS1,ANS2,ANS3,ANS4
      CHARACTER *12 SFILE,BFILE,IFILE
      INTEGER INFILE
      INTEGER NDAYS,NPPT,J,JDAY,FLAG
      LOGICAL USEJD
C     MAX LAI IS SET TO 10.0
      DATA MLAI/10.0/

C  OPTIONAL CONVERSION FUNCTIONS FOR ENGLISH UNIT INPUT FILES ONLY!
C       TO CONVERT INPUT FILES FROM ENGLISH UNITS INTO METRIC
C       CONVERSIONS ALSO NEEDED IN SUBROUTINE TRANS.
C       OUTPUT CAN BE CONVERTED TO ENGLISH UNITS VIA 'INIT.DAT' FILE
C       SEE 'README.DOC' ON FLOPPY DISK FOR DETAILS
C      FEET TO METERS
       F2M(X) = X*0.3048
C      DEGREE F TO DEGREE C
       F2C(X) = (X-32)*0.5556
C      DEGREE C TO DEGREE F
       C2F(X) = X *1.8+32.0
C      DEGREE F/FT TO DEGREE C/M LAPSE RATE
       FF2CM(X) = X*1.822


C BEGIN
      WRITE(*,'(/////////////////)')
      WRITE(*,*) '                                MTCLIM V1.0'
      WRITE(*,*) '                        -------------------------'
      WRITE(*,*) ' '
      WRITE(*,*) '          A MOUNTAINOUS TERRAIN MICROCLIMATE SIMULATOR'
      WRITE(*,*) '                              COPYRIGHT 1989.'
      WRITE(*,*) ' '
      WRITE(*,*) ' '
      WRITE(*,*) '  1) MTCLIM NEEDS A INITIALIZATION FILE DESCRIBING'
      WRITE(*,*) '     THE SITE AND BASE STATION.'
      WRITE(*,*) ' '
      WRITE(*,*) ' '
      WRITE(*,*) ' '
      WRITE(*,*) ' '
      WRITE(*,*) ' '
      WRITE(*,*) ' WHAT IS THE INITIALIZATION FILE? (12 CHAR LIMIT)'
      WRITE(*,*) ' '
      READ(*,90)IFILE
90    FORMAT(1A12)

C     FORMAT FOR INIT.DAT IS 1 VALUE FOLLOWED BY COMMENTS, PER LINE
C     REAL VALUES IN COLUMNS 1 TO 12, COMMENTS FROM 13 ONWARD.
C     READ 1 VARIABLE PER LINE BY REUSING F12.0 FORMAT STATEMENT

      OPEN(7,FILE=IFILE,STATUS='OLD')
      READ(7,100) BFILE,SFILE
 100  FORMAT(/,/,A12,/,A12)
```

```
C     ' ENGLISH(TEMPS IN F & PPT IN INCHES) OR SI(C & CM) UNITS (E OR S) ?')
      READ(7,1) ANS3
C     QUESTIONS NOW ANSWERED IN THE INIT.DAT FILE.
C     ' DO YOU HAVE DEW POINT TEMPERATURE (Y OR N) ?')
      READ(7,1) ANS0
C     ' HOW MANY PRECIP STATIONS (1 OR 2) ?')
      READ(7,*) NPPT
C     ' DO YOU WANT THRESHOLD FOR RADIATION (Y OR N) ?')
      READ(7,1) ANS1
C     ' DO YOU WANT TOTAL RAD OR AVERAGE RAD (T OR A) ?')
      READ(7,1) ANS2
C     ' USE YEARDAY(JULIAN DAY) INPLACE OF MONTH, DAY (Y OR N) ?'
      READ(7,1) ANS4
1     FORMAT(1A1)
      USEJD=(ANS4 .EQ. 'Y' .OR. ANS4 .EQ. 'y')

      READ(7,*) NDAYS

 101  FORMAT(F12.0)
      READ(7,101) SLAT,SELEV,BELEV,SASPCT,SSLOPE,SLAI
      READ(7,101) SISOH,BISOH(1),BISOH(2),SEHORZ,SWHORZ,SALBDO
      READ(7,101) TRANCF,TEMPCF,TLAPSE,MAXLAP,MINLAP,DLAPSE
      CLOSE(7)

C     CONVERT ENGLISH TO SI
      IF (ANS3 .EQ. 'E') THEN
         SELEV=F2M(SELEV)
         BELEV=F2M(BELEV)
         TLAPSE=FF2CM(TLAPSE)
         MINLAP=FF2CM(MINLAP)
         MAXLAP=FF2CM(MAXLAP)
         DLAPSE=FF2CM(DLAPSE)
      ENDIF

C     COMPUTE ATMOSPHERIC TRANSMISSIVITY
      INFILE = 8
      CALL TRANSM (INFILE,SELEV,TRAN,BFILE,NDAYS,TRANCF,
     &             ANS0,ANS3,NPPT,USEJD)

C                  INITIALIZE OUTPUT FILE
      OPEN(INFILE,FILE=BFILE,STATUS='OLD')
      OPEN(9,FILE=SFILE)
      CALL INIT9(IFILE,ANS2,ANS3,USEJD)

C     FOR EACH DAY COMPUTE AND PRINT MICROCLIMATE
      DO 11 J=1,NDAYS
C        ECHO TO SCREEN TO INDICATE PROGRAM IS WORKING
         PRINT*,J

         CALL BREAD(INFILE,JDAY,BMAX,BMIN,BDEW,BPPT,NPPT,
     &              ANS0,ANS3,USEJD)

C        THE VARIABLE FLAG IS SET TO 1 FOR SLOPED TERRAIN; FLAT TO 0
         FLAG=1.0
         CALL RAD (SLAT,SASPCT,SSLOPE,JDAY,SEHORZ,SWHORZ,TRAN,
     1             SALBDO,SRAD,SARAD,FLAG,ANS1,ANS2)
         FLAG=0
         CALL RAD (SLAT,SASPCT,SSLOPE,JDAY,SEHORZ,SWHORZ,TRAN,
     1             SALBDO,FRAD,FARAD,FLAG,ANS1,ANS2)
```

```
          CALL TEMP (BMAX,BMIN,SELEV,BELEV,SLAI,MLAI,SARAD,FARAD,
     1           TLAPSE,TEMPCF,MAXLAP,MINLAP,STEMP,SMIN,SMAX)
          CALL HUMD (BDEW,DLAPSE,STEMP,SELEV,BELEV,SHUMD)
          IF(SHUMD .GE. 100.0) SHUMD=99.0

          CALL RAIN (NPPT,BPPT,BISOH,SISOH,SPPT)

          CALL WRITE9(JDAY,SRAD,STEMP,SMAX,SMIN,SHUMD,SPPT,
     &               ANS3, USEJD)

 11    CONTINUE
       STOP
       END
C END MTCLIM


C SUBROUTINE TRANSM
       SUBROUTINE TRANSM (INFILE,SELEV,TRAN,BFILE,NDAYS,TRANCF,
     &                    ANS0,ANS3,NPPT,USEJD)
       REAL AMP(365),DRAIN(365),TRAN(365)
       REAL SELEV,TRANCF
       CHARACTER*1 ANS0,ANS3
       CHARACTER *12 BFILE
       INTEGER NPPT, INFILE, NDAYS
       LOGICAL USEJD
C
C  ORIGINAL CODE WRITTEN BY R. K. NEMANI
C  REWRITTEN BY J. C. COUGHLAN ON 4-1-89
C  MICROSOFT FORTRAN VERSION 4.1 IN STANDARD, TRANSPORTABLE FORTRAN
C
C    THIS SUBROUTINE COMPUTES TRANSMISSIVITY FOR EACH DAY BASED ON
C    BRISTOW, K.L. AND G.S. CAMPBELL 1984  On the relationship between
C    incoming solar radiation and daily maximum and minimum temperature,
C    Agric. For. Meteorol. 31, 159-66
C
C PARAMETERS
C    INFILE :UNIT NUMBER FOR BASE STATION CLIMATIC INPUT FILE
C    SELEV  :SITE ELEVATION IN METERS
C    TRAN   :ATMOSPHERIC TRANSMISSIVITY ARRAY
C    BFILE  :INPUT FILE NAME OF BASE STATION MET. DATA
C    NDAYS  :TOTAL NUMBER OF DAYS TO SIMULATE
C    TRANCF :CLEAR SKY TRANSMISSIVITY AT SEA LEVEL
C    ANS0   :FLAG TO DEW POINT PRESENT IN BFILE
C    NPPT   :NUMBER OF PREC STATIONS IN BFILE
C
C  LOCAL VARIABLES
C    TAMP  :TEMPERATURE AMPLITUDE
C    DRAIN :RAINY DAYS
C    CLTRAN:CLEAR SKY TRANSMISSIVITY
C    XTRANS:ACTUAL TRANSMISSIVITY
C    TRANCF:SEA LEVEL CLEAR SKY TRANS (D.M.GATES 1980 BIOPHYSICAL ECOLOGY)
C    PCTRAN:% TRANSMITTANCE OF CLEAR SKY POTENTIAL. TEMP AMP OF 20 = 100%
C    PPTMIN:MIN PPT FOR REDUCING ATMOSPHERIC TRANS (CM)
C    TRANMN:(CONSTANT) MINIMUM TRANSMITTANCE IN %
C    JDAY  :YEARDAY FROM INPUT FILE
C    JDAY1 :FIRST DAY IN THE INPUT FILE
C    JDAYL :LAST DAY IN THE FILE
C    KDAY  :POINTER TO ARRAYS REFERENCED BY YEARDAY
```

```
      REAL BPPTA(2), BPPT,BMAX,BMIN,BDEW,BMAX1,BMIN1,BPPT1,TAMP
      REAL DIFF,CLTRAN, PCTRAN,XTRANS
      REAL PPTMIN, TRANMN
      INTEGER K,KDAY,JDAY,JDAY1,JDAYL,I,M,J

C  CONSTANTS
      DATA PPTMIN/0.254/
      DATA TRANMN/0.1/

C  BEGIN
      K=0
      KDAY=0
      OPEN(INFILE,FILE=BFILE,STATUS='OLD')
      REWIND(INFILE)

C     READ FOR THE 1ST DAY TO INITIALIZE THE LOOP
      CALL BREAD(INFILE,JDAY,BMAX,BMIN,BDEW,BPPTA,NPPT,
     &           ANSO,ANS3,USEJD)
      IF (NPPT .EQ. 2) THEN
         BPPT = (BPPTA(1) + BPPTA(2)) / 2
      ELSE
         BPPT = BPPTA(1)
      ENDIF

C     MAKE NOTE OF THE FIRST DAY
      JDAY1 = JDAY

C     READ TO OBTAIN TEMP AMPLITUDE
      DO 12 J=1, NDAYS-1

         CALL BREAD(INFILE,KDAY,BMAX1,BMIN1,BDEW,BPPTA,NPPT,
     &              ANSO,ANS3,USEJD)
         IF (NPPT .EQ. 2) THEN
           BPPT1 = (BPPTA(1) + BPPTA(2)) / 2
         ELSE
           BPPT1 = BPPTA(1)
         ENDIF

C        COMPUTE AMPLITUDE
         TAMP = BMAX - ((BMIN + BMIN1)/2.)

C        RAINY DAY CORRECTIONS
         IF (BPPT .GT. PPTMIN) THEN
           K=K+1
           DRAIN(K) = JDAY
           TAMP =  TAMP* 0.75
         ENDIF

C        SWITCH THE VALUES FROM J+1 DAY TO J
         AMP(JDAY) = TAMP
         JDAY = KDAY
         BMAX = BMAX1
         BMIN = BMIN1
         BPPT=BPPT1
 12   CONTINUE

      JDAYL = JDAY

C     EXCEPTION FOR THE LAST DAY
 121  TAMP = BMAX - BMIN
```

```
      IF (BPPT .GT. PPTMIN ) TAMP = TAMP*0.75
      AMP(JDAY) =TAMP

C     CORRECT AMPL VALUES FOR PRE-RAINY DAYS
      DO 30 I=1,K
         KDAY = DRAIN(I)
C        CANNOT CORRECT THE 1ST AND 2ND DAY SO SKIP
         IF ((KDAY-2) .GE. JDAY1) THEN
            DIFF = AMP(KDAY-2) - AMP(KDAY-1)
            IF (DIFF.GE.2.0) AMP(KDAY-1) = AMP(KDAY-1) * 0.75
         ENDIF
30    CONTINUE

C     COMPUTE CLEAR SKY TRANSMITTANCE AT SITE (GATES 1980)
      CLTRAN = TRANCF + SELEV * 8.0E-5
      CLTRAN = AMIN1(CLTRAN,1.0)

C     COMPUTE TRANSMISSIVITY FOR EACH DAY (BRISTOW AND CAMPBELL 1984)
      DO 40 M = JDAY1, JDAYL
         PCTRAN = (1 - EXP(-0.003*(AMP(M)**2.4)))
         XTRANS = CLTRAN * PCTRAN
         TRAN(M) = AMAX1(XTRANS,TRANMN)
 40   CONTINUE

C     REWIND FILE 8 TO USE AGAIN
      REWIND(8)
      CLOSE (8)
      RETURN
      END


C  SUBROUTINE RAD
C
      SUBROUTINE RAD(SLAT,SASPCT,SSLOPE,JDAY,SEHORZ,SWHORZ,TRAN,
     1 ALBDO,RADN,ARAD,FLAG,ANS1,ANS2)
      INTEGER FLAG
      REAL SLAT,SASPCT,SSLOPE,SEHORZ,SWHORZ
      REAL ALBDO,ARAD,RADN
      REAL DEC(46),SOLCON(12),A(21),TRAN(365)
      CHARACTER*1 ANS1,ANS2

C     VALIDATED TO BUFFO BY JCC ON 4-19-89
C     RAD COMPUTES INCIDENT SHORTWAVE RADIATION AND
C     NET SHORTWAVE RADIATION FOR ANY GIVEN DAY BASED ON SURFACE
C     CHARACTERISTICS, SUN-EARTH GEOMETRY, TRANSMISSIVITY.
C
C  VARIABLES
C     SLAT: SITE LATITUDE   DEGREES
C     SASPECT:SITE ASPECT  %
C     SSLOPE:SITE SLOPE  %
C     JDAY: CURRENT YEARDAY
C     SEHORZ:SITE EAST HORIZON IN DEGREES FROM 0
C     SWHORZ:SITE WEST HORI IN DEGREES FROM 0
C     TRAN:TRANSMISSIVITY ARRAY   %
C     ALBDO:SITE ALBEDO   %
C     ARAD:ABSORBED RADIATION, W/M2
C     RADN:INCIDENT RADIATION  W/M2
C     FLAG:1 MEANS SLOPING TERRAIN, 0 MEANS FLAT SURFACE.
C     ANS1:THRESHOLD RADIATION OF 70 W/M^2
C     ANS2:TOTAL RADIATION IF = TO T   KJ/M^/DAY
```

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C          ELSE DAYLIGHT AVERAGE   W/M^2
C
C
C  ORIGINAL CODE WRITTEN BY R. K. NEMANI
C  REWRITTEN BY J. C. COUGHLAN ON 4-1-89
C  MICROSOFT FORTRAN VERSION 4.1 IN STANDARD, TRANSPORTABLE FORTRAN
C
C  THIS CODE CAN BE OPTIMIZED TO THE POINT WHERE IT CUTS TOTAL PROGRAM
C  EXECUTION TIME TO HALF OF THE PRESENT.  REMOVE AS MUCH FROM THE DO
C  LOOP AS POSSIBLE.  THE DO LOOP INCREMENTS 10 MINUTES FOR A 24 HOUR
C  DAY.  SOME CALCULATIONS CAN BE DONE ONCE OUTSIDE THE LOOP I.E.
C  COS(DSLOPE), AND SAVED IN A VARIABLE TO BE USED IN THE LOOP.  WE
C  HAVE KEPT IT LESS EFFICIENT TO REDUCE COMPLEXITY.  EFFICIENT CODE
C  IS LESS READABLE, USUALLY.  ALSO, HAVE HARDWARE SUPPORT FOR MATH
C  REALLY HELPS TOO, ESP. FOR TRIG. FUNCTIONS. -JCC
C
C   LOCAL VARIABLE LIST:
C     SOL   =SOLAR CONSTANT DERIVED FROM SOLCON ARRAY
C     AM    =OPTICAL AIR MASS FOR ANGLES > 21 DEGREES
C     A     =OPTICAL AIR MASS ARRAY FOR ANGLES BETWEEN
C             0 AND 21 DEGREES ABOVE HORIZON
C     DECL  =DECLINATION
C     JDAY  =DAY OF YEAR
C     ASP   =ASPECT IN DEGREES
C     DSLOP =SLOPE IN DEGREES
C     H     =ANGLE OF SUN FROM SOLAR NOON
C     TRAN  =TRANSMISSIVITY CONSTANT
C     TRAM  =TRANSMISSIVITY CORRECTED FOR AIR MASS
C     NNH   =CALCULATION INTERVAL IN SECONDS. 600 = 10 MINUTES
C     NC    =SECONDS IN ONE DAY (24 HOURS)
C     N     =NUMBER OF INTERVALS OF LENGTH NNH IN ONE DAY
C     DT    =DIRECT SOLAR PERPENDICULAR TO SUN ON THE
C             OUTSIDE OF ATMOSPHERE FOR INTERVAL (KJ/M**2)
C     ETF   =DIRECT SOLAR ON OUTSIDE OF ATMOSPHERE
C             PARALLEL TO EARTHS SURFACE FOR INTERVAL
C     GRAD  =TOTAL DAILY RADIATION AT GIVEN LOCATION (KJ/M**2)
C     HRAD  =DIRECT SOLAR ON EARTHS SURFACE (FLAT)       "
C     TDIF  =TOTAL DAILY DIFFUSE RADIATION               "
C     DIFRAD=DIFFUSE ON SLOPE FOR INTERVAL               "
C     DRAD  =DIRECT ON SLOPE FOR INTERVAL                "
C     CZA   =COSINE ZENITH ANGLE
C     CBSA  =COSINE BEAM SLOPE ANGLE
C     GLOBF =GLOBAL RADIATION, DETERMINING DIFFUSE
C     DIFFL =DIFFUSE ON FLAT FOR INTERVAL
C     DAYL  =DAYLENGTH (HOURS)
C     ALBDO =ALBEDO
C
C
C  LOCAL VARIABLES
      INTEGER NNH,NC,N,MO,IDEC,NH,K,ML
      REAL CONV,X,ASP,DLAT,SLOPE,DSLOP,XTRAN,DECL,GRAD,TDIF
      REAL DAYL2,DH,CZA,H,AM,TRAM,DT,ETF,HRAD,GLOBF,DIFFL,CBSA
      REAL DRAD,SE,DIFRAD,RADT,AVERAD,DAYL,SOL,TDRAD
C
C  CONSTANTS
      DATA A/2.90,3.05,3.21,3.39,3.69,3.82,4.07,4.37,4.72,5.12
     1,5.60,6.18,6.88,7.77,8.90,10.39,12.44,15.36,19.79,26.96
     2,30.00/
      DATA DEC/-23.,-22.,-21.,-19.,-17.,-15.,-12.,-9.,-6.,-3.,
     10.,3.,6.,9.,12.,14.,17.,19.,21.,22.,23.,23.5,23.5,23.,
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     221.5,20.,18.,16.,14.,12.,9.,6.,3.,0.,-3.,-6.,-9.,-12.,
     3-15.,-17.,-19.,-21.,-22.,-23.,-23.5,-23.5/
      DATA SOLCON/1.445,1.431,1.410,1.389,1.368,1.354,1.354
     1,1.375,1.403,1.424,1.438,1.445/
C
C  FUNCTIONS
C     CONVERSION STATEMENT FUNCTION FOR DEGREES TO RADIANS
      CONV(X)=X/57.296
C
C  BEGIN
C     SET THE SLOPE & ASPECT VALUES DEPENDING ON THE FLAG VALUE
      IF (FLAG .GT.0) THEN
         ASP=conv(SASPCT)
         SLOPE=SSLOPE
      ELSE
         ASP=0
         SLOPE=0
      ENDIF

C     CONVERT PERCENT SLOPE TO DEGREES and to radians
      DLAT=conv(SLAT)
      DSLOP=ATAN(SLOPE/100.)*57.29
      DSLOP=conv(DSLOP)
      XTRAN=TRAN(JDAY)
      NNH=600
      NC=86400
      N=IFIX(NC/NNH+1.)
      DAYL=0.
      MO=IFIX(JDAY/30.+1.)
      IF (MO.GT.12)MO=12

C     SOLCON ARRAY IS IN UNITS OF KW/M**2
      SOL=SOLCON(MO)
      IDEC=IFIX(1.+JDAY/8.)
      DECL=conv(DEC(IDEC))
      GRAD=0.
      TDIF=0.
      TDRAD=0.
      NH=0
      DAYL2=0.

C     DO LOOP INCREMENTS 10 MINUTES, STOPS AFTER 24 HOURS
      DO 11 K=1,N
         NH=NH+NNH
C        DETERMINE ANGLE FROM SOLAR NOON
         DH=(NH-43200)*.0041667
         h=conv(dh)
         CZA=COS(DECL)*COS((DLAT))*COS((H))+SIN((DECL))
     1   *SIN((DLAT))
         IF(CZA.GT. 0.) THEN
C
C           DAYLENGTH BASED ON SOLAR ELEVATION ABOVE A FLAT HORIZON
            DAYL2=DAYL2+(NNH/3600.)
C
C           NEXT 6 LINES, DETERMINE OPTICAL AIR MASS
            AM=1./(CZA+.0000001)
            IF(AM.GT.2.9) THEN
               ML=IFIX(ACOS(CZA)/.0174533)-69
               IF(ML.LT.1)ML=1
               IF(ML.GT.21)ML=21
```

```
                  AM=A(ML)
               ENDIF
C
               TRAM=XTRAN**AM
               DT=SOL*NNH
               ETF=CZA*DT
               HRAD=ETF*TRAM
               DT=DT*TRAM
               GLOBF=SQRT(HRAD*ETF)
               DIFFL=GLOBF*(1.-GLOBF/ETF)
               CBSA=-SIN(DSLOP)*SIN(ASP)*SIN(H)
     1         *COS(DECL)+(-COS(ASP)*SIN(DSLOP)
     2         *SIN(DLAT)+COS(DSLOP)*COS(DLAT))
     3         *COS(DECL)*COS(H)+(COS(ASP)*SIN(DSLOP)
     4         *COS(DLAT)+COS(DSLOP)*SIN(DLAT))
     5         *SIN(DECL)
               IF(CBSA.GE.0.) THEN
                  DRAD=CBSA*DT
C                 THE FOLLOWING THREE LINES COMPUTES A TOPOGRAPHIC REDUCTION OF
C                 DIRECT RADIATION
C                 EHE = EAST HORIZON ELEVATION (DEGREES)
C                 WHE = WEST HORIZON ELEVATION (DEGREES)
                  SE=1.57-ACOS(CZA)
                  IF(DH.LT.0.AND.SE.LT.CONV(SEHORZ))DRAD=0.
                  IF(DH.GT.0.AND.SE.LT.CONV(SWHORZ))DRAD=0.
               ELSE
                  DRAD=0
               ENDIF

               DIFRAD=DIFFL*(COS((DSLOP*.5))**2.)
               RADT=(DRAD+DIFRAD)/FLOAT(NNH)
C
C              THE FOLLOWING PROVIDES A MINIMUM RADIATION THRESHOLD OF
C              70 W/M**2 (0.1 LY/MIN) FOR DAYLENGTH AND RADIATION SUMMATION.
C
               IF(ANS1.EQ.'Y') THEN
                  IF(RADT.GT.0.07) THEN
                     DAYL = DAYL + (NNH/3600.)
                     GRAD = GRAD + DRAD + DIFRAD
                     TDIF = TDIF + DIFRAD
                     TDRAD = TDRAD + DRAD
                  ENDIF
               ELSE
                  DAYL = DAYL + (NNH/3600.)
                  GRAD = GRAD + DRAD + DIFRAD
                  TDIF = TDIF + DIFRAD
                  TDRAD = TDRAD + DRAD
               ENDIF
            ENDIF
11       CONTINUE
         IF(ANS2.EQ.'T') THEN
            RADN = GRAD
            ARAD = RADN * (1- ALBDO)
         ELSE
            AVERAD=(GRAD/(DAYL*3600.))
C           CONVERT KW/M**2 to W/M**2
            RADN = AVERAD * 1000.0
            ARAD = RADN * (1-ALBDO)
         ENDIF
         RETURN
```

```
      END


C  SUBROUTINE TEMP
C
      SUBROUTINE TEMP (BMAX,BMIN,SELEV,BELEV,SLAI,MLAI,SARAD,
     1      FARAD,TLAPSE,TEMPCF,MAXLAP,MINLAP,STEMP,SMIN,SMAX)

      REAL BMAX, BMIN, SELEV, BELEV, SLAI, MLAI, SARAD, TEMPCF
      REAL FARAD, TLAPSE, MAXLAP, MINLAP,STEMP, SMIN, SMAX
C
C     TEMP COMPUTES SITE DAYLIGHT AVERAGE TEMPERATURE, AND SITE MAX &
C     MIN TEMPS BASED ON BASE STATION DATA AND THEN CORRECTS IT FOR
C     ELEVATION, SLOPE AND ASPECT.
C
C PARAMETER LIST
C   BMAX   :BASE STATION MAX TEMP
C   BMIN   :BASE STATION MIN TEMP
C   SELEV  :SITE ELEVATION IN METERS
C   BELEV  :BASE ELEVATION IN METERS
C   SLAI   :SITE LAI (ALL SIDES)
C   MLAI   :MAXIMUM LAI (ALL SIDES) FOR MTCLIM ALGORITHMS
C   SARAD  :SITE RADIATION KJ/M^2/DAY
C   FARAD  :FLAT SURFACE RADIATION AT SITE KJ/M^2/DAY
C   TLAPSE :LAPSE RATE FOR DAYLIGHT AVE TEMP  C/1000M
C   TEMPCF :CONSTANT FOR DAYLIGHT AVE. TEMP (RUNNING ET.AL. EQ. 1)
C   MAXLAP :LAPSE RATE FOR MAX TEMPS C/1000M
C   MINLAP :LAPSE RATE FOR MIN TEMPS C/1000M
C   STEMP  :SITE DAYLIGHT AVE TEMP C
C   SMIN   :SITE MIN TEMP C
C   SMAX   :SITE MAX TEMP C
C
C LOCAL VARIABLE LIST
C   MLAPSE: LAPSE RATE FOR NIGHT MIN TEMPERATURES
C   DAYLT: DAYLIGHT AVERAGE TEMPERATURE
C   TSYNOP: SYNOPTIC TEMPERATURE AT THE SITE
C   RADRAT: RATIO OF FLAT AND SLOPE RADIATION
C   TADD : TEMPERATURE INCREMENT FOR SOUTH SLOPES
C   TSUB : TEMPERATURE DECREMENT FOR NORTH SLOPES
C   MLAI : MAXIMUM LAI (ALL SIDES)

C  LOCAL VARIABLES
      REAL LAI,TMEAN
      REAL DAYLT,DELEV,TSYNOP,RADRAT,TSUB,TADD

C IF SITE LAI > MAX LAI THEN USE MAX LAI IN EQUATIONS BELOW
      IF (SLAI .GT. MLAI) THEN
        LAI = MLAI
      ELSE
        LAI = SLAI
      ENDIF

C     COMPUTE DAYLIGHT AVERAGE TEMP
      TMEAN= (BMAX+BMIN)/2.0
      DAYLT= ((BMAX-TMEAN)*TEMPCF) + TMEAN

C                CORRECT FOR LAPSE RATE
      DELEV = SELEV-BELEV
      TSYNOP = DAYLT - TLAPSE * (DELEV / 1000.0)
      SMIN = BMIN - (DELEV/1000.0 * MINLAP)
```

```
      SMAX = BMAX - (DELEV/1000.0 * MAXLAP)

C                COMPUTE THE RATIO OF SLOPE AND FLAT RADIATION
      RADRAT = SARAD/FARAD

C                ADJUST SYNOPTIC TEMP TO OBTAIN SLOPE TEMP
C     ADDITIONS MADE ON 10/88 TO ADJUST MAX TEMPS TO RADIATION.
C     NOT VALIDATED BY LITERATURE.
C     NOT ADJUSTING MINIMUM TEMPERATURE BECAUSE LONGWAVE NIGHT ADJUSTMENT.

      IF (RADRAT.LT.1.0) THEN
         TSUB=((1/RADRAT)*(1+(LAI/MLAI)))
         STEMP = TSYNOP -  TSUB
         SMAX = SMAX - TSUB
      ELSE
         TADD=(RADRAT* (1-(LAI/MLAI)))
         STEMP = TSYNOP + TADD
         SMAX = SMAX + TADD
      ENDIF
      RETURN
      END



      SUBROUTINE HUMD (BDEW,DLAPSE,STEMP,SELEV,BELEV,SHUMD)
      REAL BDEW, DLAPSE,STEMP,SELEV,BELEV,SHUMD
C  PARAMETERS
C    BDEW    :BASE STATION BEW POINT C
C    DLAPSE :DEW POINT LAPSE RATE
C    STEMP   :DAYLIGHT AVE. TEMP. LAPSE RATE
C    SELEV   :SITE ELEVATION IN METERS
C    BELEV   :BASE ELEVATION IN METERS
C    SHUMD   :SITE HUMIDITY %
C  HUMD COMPUTES RELATIVE HUMIDITY BASED ON BASED
C  ON BASE STATION DEW POINT
C
C  LOCAL VARIABLES
C    SDEW    :SITE DEW POINT  C
C    ES      :AMBIENT VAPOR DENSITY
C    ESD     :SATURATED VAPOR DENSITY
      REAL SDEW,ES,ESD

C     CORRECT DEW PNT FOR LAPSE
      SDEW = BDEW - (DLAPSE * ((SELEV-BELEV)/1000.))
C     COMPUTE RELATIVE HUMIDITY
      ES = 6.1078 * EXP((17.269*SDEW)/(237.3 + SDEW))
      ESD = 6.1078 * EXP((17.269 * STEMP)/(237.3 + STEMP))
      SHUMD=(ES/ESD) * 100.0
      RETURN
      END



      SUBROUTINE RAIN (NPPT,BPPT,BISOH,SISOH,SPPT)
      INTEGER NPPT
      REAL BISOH(2),SISOH,SPPT,BPPT(2)
      REAL RAT1,RAT2

C     NPPT: NUMBER OF BASE PPT STATIONS
```

```
C     THIS SUBROUTINE COMPUTES SITE PRECIPITATION BY MULTIPLYING
C     THE BASE STATION PRECIP WITH THE RATIO OF BASE AND SITE
C     ISOHYETS.

C     COMPUTE RATIO OF THE ISOHYTE(S)
      RAT1 = SISOH/BISOH(1)
      IF (NPPT .EQ. 2) THEN
         RAT2 = SISOH/BISOH(2)
         SPPT = ( BPPT(1)*RAT1 + BPPT(2)*RAT2 ) / 2.0
      ELSE
         SPPT = RAT1*BPPT(1)
      ENDIF
      RETURN
      END


       SUBROUTINE MONDAY(JDAY,MON,DAY)
       INTEGER JDAY,MON,DAY
       INTEGER DAYS(12)
       DATA DAYS/31,28,31,30,31,30,31,31,30,31,30,31/
       DAY=JDAY
       MON = 1
10     IF(DAY .GT. DAYS(MON) ) THEN
          DAY=DAY-DAYS(MON)
          MON = MON+1
          GO TO 10
       ENDIF
       RETURN
       END


       REAL FUNCTION YEARDAY(MON,IDATE)
       INTEGER DAYS(12), I,JDAY,MON
       DATA DAYS/31,28,31,30,31,30,31,31,30,31,30,31/
       JDAY = 0
       DO 10 I = 1, (MON-1)
          JDAY= JDAY+DAYS(I)
10     CONTINUE
       JDAY=JDAY+IDATE
       YEARDAY=JDAY
       RETURN
       END


       SUBROUTINE WRITE9(JDAY,SRAD,STEMP,SMAX,SMIN,SHUMD,SPPT,
     & ANS3, USEJD)
       INTEGER JDAY,DAY,MON
       REAL SRAD,STEMP,SMAX,SMIN,SHUMD,SPPT,C2F,X
       LOGICAL USEJD
       CHARACTER*1 ANS3
C      DEGREE C TO DEGREE F
       C2F(X) = X *1.8+32.0

       IF (ANS3 .EQ. 'E') THEN
c        CONVERT TEMPERATURES TO DEG F IF INDICATED
            STEMP = C2F(STEMP)
            SMIN = C2F(SMIN)
            SMAX = C2F(SMAX)
            SPPT = SPPT/2.54
       ENDIF
```

```
      IF (USEJD) THEN
        WRITE(9,110) JDAY,SRAD,STEMP,SMAX,SMIN,SHUMD,SPPT
110     FORMAT(1X,I3,2X,F8.2,4(F6.0),F5.2)
      ELSE
        CALL MONDAY(JDAY,MON,DAY)
        WRITE(9,111) MON,DAY,SRAD,STEMP,SMAX,SMIN,SHUMD,SPPT
111     FORMAT(1X,I2,2X,I3,2X,F8.2, 4(F6.0),F5.2)
      ENDIF
      RETURN
      END


      SUBROUTINE INIT9(IFILE,ANS2,ANS3,USEJD)
      CHARACTER*1 ANS2,ANS3
      CHARACTER*80 LINE1, LINE3
      CHARACTER*17 LINE2
      CHARACTER*12 IFILE
      LOGICAL USEJD

C IDENTIFY THE OUTPUT FILE
      WRITE(9,*)' MTCLIM OUTPUT FILE'
      WRITE(9,*)' A LISTING OF INITIALIZATION FILE FOLLOWED BY OUTPUT:'
      WRITE(9,*)

C LIST INITIALIZATION FILE IN OUTPUT FILE
      OPEN(UNIT=7,FILE=IFILE)
2     READ(7,1,END=10) LINE1
1        FORMAT(1A80)
         WRITE(9,1)LINE1
         GO TO 2
10    CONTINUE
      WRITE(9,*)

C SET UP HEADINGS FOR OUTPUT FILE
      IF (USEJD) THEN
         LINE1='JDAY  RADIATION  STEMP MAXT  MINT  RH   PPT'
      ELSE
         LINE1='MON  DAY RADIATION  STEMP MAXT  MINT  RH   PPT'
      ENDIF

      IF (ANS2 .EQ. 'T') THEN
        LINE2= '        KJ/M**2 '
      ELSE
        LINE2= '        W/M**2 '
      ENDIF

      IF (ANS3 .EQ. 'E') THEN
        LINE3=LINE2//'F     F     F     %     INCHES'
      ELSE
        LINE3=LINE2//'C     C     C     %     CM '
      ENDIF

      WRITE(9,111)LINE1,LINE3
111   FORMAT(1A80)

      RETURN
      END

C  SUBROUTINE BREAD: READ BASE STATION DATA.
```

```
      SUBROUTINE BREAD(INFILE,JDAY,BMAX,BMIN,BDEW,BPPT,NPPT,
     &                 ANSO,ANS3,USEJD)
      INTEGER INFILE, JDAY, NPPT
      REAL BMAX,BMIN
      REAL BPPT(2)
      CHARACTER*1 ANSO, ANS3
      LOGICAL USEJD
C  VARIABLES
C       INFILE: INTEGER UNIT NUMBER OF BASE STATION CLIMATIC INPUT FILE
C       JDAY: YEARDAY
C       BMAX: MAXIMUM TEMPERATURE
C       BMIN: MINIMUM TEMPERATURE
C       BDEW: DEW POINT TEMPERATURE
C       NPPT: NUMBER OF BASE STATIONS 1 OR 2
C       ANSO: IS DEW POINT SUPPLIED IN FILE
C             IF NOT THEN SET IT TO NIGHT MINIMUM TEMPERATURE.
C       ANS3: IS INPUT IN ENGLISH OR SI UNITS, 'E' = ENGLISH SO CONVERT TO SI
C
C    FUNCTION F2C: DEGREE F TO DEGREE C
      REAL F2C,X,YEARDAY
      INTEGER DAY, MON
      F2C(X) = (X-32)*0.5556

C BEGIN
      IF (USEJD) THEN
        IF(ANSO.EQ.'Y') THEN
          IF(NPPT .EQ. 1) THEN
            READ(INFILE,*) JDAY, BMAX, BMIN, BDEW, BPPT(1)
            BPPT(2) = 0.0
          ELSE
            READ(8,*) JDAY, BMAX, BMIN, BDEW, BPPT(1), BPPT(2)
          ENDIF
        ELSE
          IF(NPPT .EQ. 1) THEN
            READ(INFILE,*) JDAY, BMAX, BMIN, BPPT(1)
            BPPT(2) = 0.0
            BDEW=BMIN
          ELSE
            READ(INFILE,*) JDAY, BMAX, BMIN, BPPT(1), BPPT(2)
            BDEW = BMIN
          ENDIF
        ENDIF
      ELSE
        IF(ANSO.EQ.'Y') THEN
          IF(NPPT .EQ. 1) THEN
            READ(INFILE,*) MON,DAY, BMAX, BMIN, BDEW, BPPT(1)
            BPPT(2) = 0.0
          ELSE
            READ(8,*) MON,DAY, BMAX, BMIN, BDEW, BPPT(1), BPPT(2)
          ENDIF
        ELSE
          IF(NPPT .EQ. 1) THEN
            READ(INFILE,*) MON,DAY, BMAX, BMIN, BPPT(1)
            BPPT(2) = 0.0
            BDEW=BMIN
          ELSE
            READ(INFILE,*) MON,DAY, BMAX, BMIN, BPPT(1), BPPT(2)
            BDEW = BMIN
          ENDIF
        ENDIF
```

```
        JDAY=YEARDAY(MON,DAY)
      ENDIF

      IF (ANS3 .EQ. 'E') THEN
C CONVERT ENGLISH UNITS TO SI
         BPPT(1) = BPPT(1) * 2.54
         BPPT(2) = BPPT(2) * 2.54
         BMAX = F2C(BMAX)
         BMIN = F2C(BMIN)
         BDEW = F2C(BDEW)
      ENDIF

      RETURN
      END
C
C ---------------- END LISTING -----------------
```

APPENDIX B: SINE FORM FOR AVERAGING TEMPERATURE

The assumption that daylight average temperature is described by three quadrants of the sine function is illustrated in figure 12. Minimum temperature usually occurs at or close to sunrise, maximum temperature occurs near midday, and temperature at sunset is somewhere in between maximum and minimum. Using this assumption and integrating the area under the curve the value for TEMCF is 0.212.

To test if the sine form weighted air temperature (T_{ave}) is a more accurate measure of daylight air temperature than the normally used arithmetic mean average air temperature (T_{mean}), 120 days of hourly measured meteorological data from Fraser Experimental Forest, Colorado, were used as a benchmark. Regressions of the T_{ave} and T_{mean} data against the hourly averaged daylight air temperatures were calculated and found to be:

$$T_{ha} = -1.14 + 1.12\ T_{ave} \quad r^2 = 0.93; \qquad n = 120 \text{ days}$$

and:

$$T_{ha} = 0.74 + 1.20\ T_{mean} \quad r^2 = 0.88; \qquad n = 120 \text{ days}$$

where:

T_{ha} = daylight air temperature, hourly averaged.

The sine form weighted average more closely approximated the benchmark hourly averaged daylight air temperature as evidenced by a higher correlation coefficient and a slope closer to 1.0.

Observation of diurnal temperature traces for sites at Coram and other locations in the Northern Rocky Mountains indicate that temperature rises more rapidly after sunrise than given by the sine function (fig. 12). The maximum temperature may be shifted to the left, and the peak widened (fig. 12). Actual sunset is at $3\pi/4$, thus the daylight period is shorter than assumed by the sine function (fig. 12). The net result is that the average daylight temperatures are greater than estimated by the sine function and TEMCF is greater (0.45) as shown in figure 12 for an observed data set.

Observed daylight average data (based on hourly readings) for several sites (Lubrecht, Coram 12, 14, 33, and 23) were used to calculate TEMCF. Two procedures were used. The first substituted observed daily average values into equation 1, then solved for TEMCF. The second used a regression procedure with the observed daily average values to provide a least squares estimate for TEMCF. When data for a whole season were used, calculated values ranged from 0.30 to 0.60. Values for these analyses averaged close to 0.45 for TEMCF; thus, this value was used in our model analyses to compare predicted with observed daylight average temperatures.

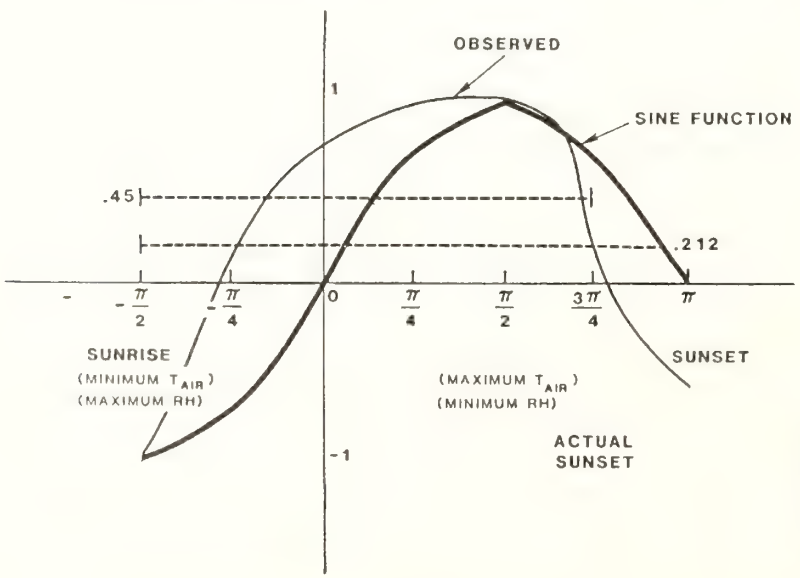


Figure 12—The sine wave used to approximate daylight average temperature and the observed pattern of temperature amplitude.

APPENDIX C: ESTIMATING DAILY DEWPOINT TEMPERATURE

Comparison of spatial differences in dewpoint are made for two locations in western Montana that are 100 miles apart (fig. 13). There appears to be a good relationship with the slope of the regression line very close to 1.0 and the intercept near 0.0, with most points fairly close to the line.

The assumption that dewpoint is equal to night minimum temperature is tested using two data sets in western Montana. Results of regression analyses for data at Lubrecht in 1984 are shown in figure 14. The relationship is quite good, with an r^2 of 0.85. The figure does show that for some days during the summer dewpoint temperature can be much less than night minimum. Results from the Missoula NWS data were nearly identical ($r^2 = 0.88$, slope = 0.88, and intercept = 0.47) to the results from Lubrecht. Although errors can occur for individual days, the relationship is strong enough that night minimum temperature is a reasonable estimator of dewpoint temperature.

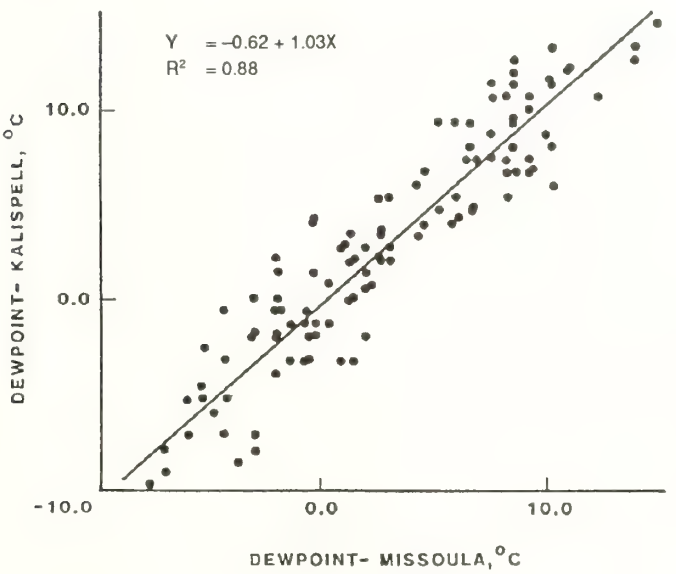


Figure 13—The relationship between dewpoint measured at the Missoula, MT, airport and the Kalispell, MT, airport 120 miles away, for 204 days from April-November 1983, as a test of regional equivalence of daily absolute humidity.

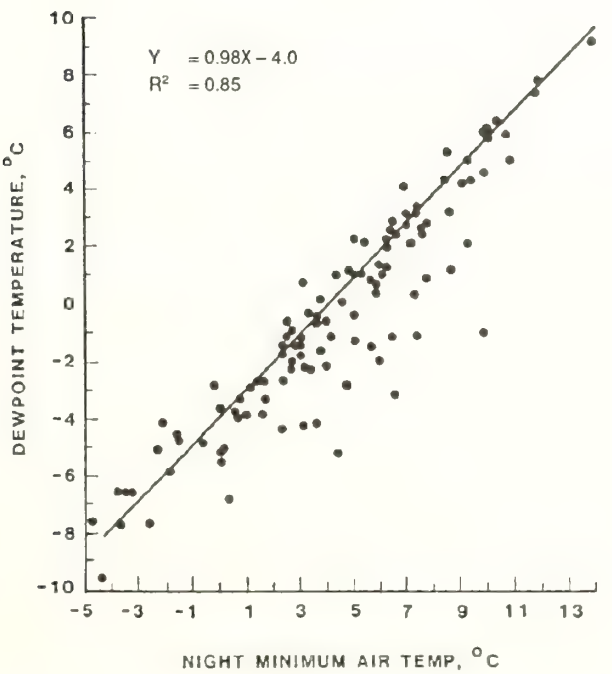


Figure 14—The relationship between dewpoint and night minimum air temperature found for the period Year Day 65-299, 1984, at Lubrecht Experimental Forest in western Montana. This test was done to determine how accurately dewpoint can be estimated from night minimum temperature if humidity data is not available.

APPENDIX D: EQUATIONS FOR CALCULATING SOLAR RADIATION

Equations for Calculating Atmospheric Transmissivity

The equations for calculating atmospheric transmissivity in MTCLIM are a modification of the equations from Bristow and Campbell, 1984. The equations are used to calculate a multiplier that is used for calculating incoming solar radiation.

The equation used to calculate maximum clear sky atmospheric transmittance corrected for elevation is:

$$A = \text{TRANCF} + (\text{SELEV})\ (0.00008) \tag{1}$$

where A is the maximum clear sky atmospheric transmittance of the study area or region, TRANCF is the clear sky transmittance of the site equivalent to sea level (assumed to be 0.65 for western Montana), and SELEV is elevation of the site in meters. The value 0.00008 is the correction for increasing transmittance with increases in elevation.

Clear sky transmittance (A) is used to calculate atmospheric transmittance as a function of daily air temperature range by the equation from Bristow and Campbell (1984):

$$T_t = A(1-\exp(-B\Delta TC)) \tag{2}$$

where T_t is the daily total atmospheric transmittance, A is the maximum clear sky transmittance from equation (1), ΔT is the daily range of air temperature, and B and C are empirical coefficients that determine how soon maximum T_t is achieved as ΔT increases. In MTCLIM $B = -0.0030$ and $C = 2.4$, based on conditions for western Montana and northern Idaho. Bristow and Campbell discuss methods for determining the value for B and C. In their paper, B changed with season (0.004 in summer and 0.010 in winter) and C was held constant at 2.4.

The daily range of air temperature (ΔT) is calculated by the equation:

$$\Delta T_j = T_{\text{max}j} - (T_{\text{min}j} + T_{\text{min}j+1})/2 \tag{3}$$

where ΔT_j is the daily range of temperature for the jth day, $T_{\text{max}j}$ is the maximum temperature on the jth day, $T_{\text{min}j}$ is the minimum temperature on the jth day, and $T_{\text{min}j}+1$ is the minimum temperature on the day following the jth day. Once ΔT_j is calculated from equation (3), it is corrected for rainy periods. If it rained on the jth day ΔT_j from equation (3) was corrected, making $\Delta T = 0.75\ \Delta T_j$. If ΔT_{j-1} was less than ΔT_{j-2} by more than 2 °C, $\Delta T_{j-1} = 0.75\ \Delta T_{j-1}$. In this situation it is assumed that the cloudy conditions began on day $j-1$, resulting in a large drop in incoming radiation. See Bristow and Campbell, 1984 for more details.

Equations for Calculating Potential Incoming Radiation

The equations used to calculate potential incoming radiation are based on Garnier and Ohmura (1968), Buffo and others (1972), and Swift (1976). The basic equation calculates incoming radiation on the slope:

$$Q_s = Is_s + D_s \tag{4}$$

where Q_s is the total incoming radiation on a slope (kJ/m^2) at the earth's surface, Is_s is the direct beam radiation on a slope at the earth's surface, and D_s is the diffuse radiation at the surface.

The direct beam radiation Is_s at the surface is calculated by:

$$Is_s = \cos\phi(R_o N * T_t^{AM}) \tag{5}$$

where R_o is the solar constant (kW/m^2) above the atmosphere, with an average value for each month; N is the time interval for calculation in seconds; T_t is the daily total transmittance from equation (2); and AM is the optical air mass calculated by

$$AM = 1.0/\cos\theta + 1.0 \times 10^{-7} \tag{6}$$

where $\cos\theta$ is the cosine of the zenith angle (CZA in the code in appendix A) calculated by equation (11). If AM is >2.9 then:

$$ML = \text{IFIX}(A_m \cos(\cos\theta)/0.0174533) - 69 \quad (7)$$

where IFIX converts a real value into an integer, A_m is the optical air mass value in an array (data values are in code in appendix A) for angles between 0 and 21 degrees above the horizon. If ML is <1, ML is set equal to 1.0; if ML is >21, ML is set equal to 21, then AM is equal to $A_m * ML$.

$\cos\phi$ (CBSA in the code in appendix A) is the cosine of the beam slope angle and is given by

$$\cos\phi = -\sin S*\sin AZ*\sin H*\cos\delta + (-\cos AZ*\sin S*\sin L+\cos S*\cos L)* \cos\delta*\cos H + (\cos AZ*\sin S*\cos L + \cos S*\sin L)*\sin\delta \quad (8)$$

where S is the slope in degrees, AZ is aspect in degrees, H is hour angle calculated by $H = (NH - 43200)*0.0041667$ (NH is time of day), δ is declination of the sun based on time of year (values are given in code in appendix A for 8-day periods through the year as the variable DEC), and L is latitude in degrees.

The diffuse radiation at the surface on a slope is calculated by:

$$D_s = D_f * \cos(S/2)^2 \quad (9)$$

where D_f is the diffuse radiation on a flat surface, and S is the slope in degrees.

$$D_f = ((\cos\theta\, R_o N)^2 T_t^{AM})^{0.5} * (1 - \cos\theta\, R_o N T_t^{AM})^{0.5} \quad (10)$$

where R_o, N, T_t, and AM have been defined for equations 2, 5, 6, and 7. $\cos\theta$ is the cosine of the zenith angle (CZA in the code in appendix A) of the sun given by:

$$\cos\theta = \cos\delta*\cos L*\cos H + \sin\delta*\sin L \quad (11)$$

where δ, L, and H are as defined for equation 8.

The above equations calculate total radiation or average radiation from sunrise to sunset.

Notation

Q_s	Total incoming radiation on a sloping surface (GRAD in appendix A)
Is_f	Direct beam radiation on a flat surface (HRAD in appendix A)
Is_s	Direct beam radiation on a sloping surface (DRAD in appendix A)
D_f	Diffuse radiation on a flat surface (DIFFL in appendix A)
D_s	Diffuse radiation on a sloping surface (DIFRAD in appendix A)
$\cos\phi$	cosine beam slope angle (CBSA in appendix A)
$\cos\theta$	cosine zenith sun angle (CZA in appendix A)
δ	declination angle of sun (DECL in appendix A)
L	latitude of site in degrees (SLAT in appendix A)
H	hour angle of sun from solar noon (H in appendix A)
AZ	aspect of site in degrees (SASPCT in appendix A)
S	slope in degrees (SSLOPE in appendix A)
R_o	solar constant (SOLCON in appendix A)
T_t	atmospheric transmissivity constant (TRAN in appendix A)
AM	optical air mass (AM in appendix A)
A	maximum clear sky atmospheric transmittance
B	empirical coefficient (–0.0030 in MTCLIM)
C	empirical coefficient (2.4 in MTCLIM)
TRANCF	clear sky transmittance equivalent to sea level
SELEV	elevation of site in meters

T	air temperature
ΔT	daily range of air temperature
T_{max}	maximum temperature for a day
T_{min}	minimum temperature for a day
N	time interval

APPENDIX E: CALCULATING HORIZON ANGLES FROM A TOPOGRAPHIC MAP

The angles to the east and west horizons, if they have not been measured, can be calculated using a topographic map. These angles are used in MTCLIM to truncate direct-beam incoming radiation at sunrise and sunset to account for blockage of the sun by ridges, tree lines, or other obstacles that block the sun. Figure 15 is a simple diagram of an elevation view of a site on a flat with ridges to the east and west. The angle θ in degrees needs to be calculated and entered in the INIT.DAT file as EAST-HORIZ and WEST-HORIZ. The angle θ is calculated using the following relation

$$\theta = \arctan h/d \tag{1}$$

where h is the elevation difference (feet) between the site and the ridge top blocking the sun, and d is the horizontal distance (feet) from the site to the ridge top blocking the sun. The elevation difference h is obtained from a topographic map by calculating the difference in elevation, given by the contours, between the ridge, or other obstacle, and the site. The horizontal distance d is a straight-line distance on the map between the site and ridge top, converted to feet using the appropriate scale for the map.

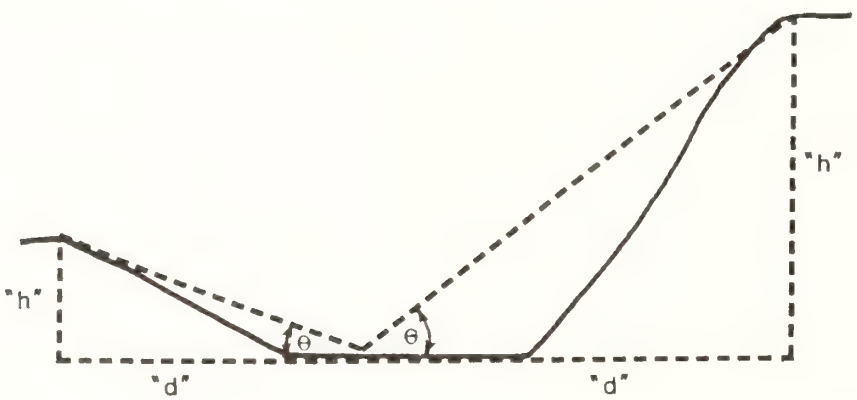


Figure 15—Measurements needed to calculate east and west horizon angles from a topographic map.

APPENDIX F: EQUATIONS FOR CALCULATING PRECIPTATION

The equations used to calculate daily precipitation at the site are based on daily precipitation at one base station, or two base stations if data are available. The equation using one base station is

$$P_s = P_{B1} * A_s / A_B \quad (1)$$

and the equation using two base stations is

$$P_s = (P_{B1} * A_s / A_{B1} + P_{B2} * A_s / A_{B2}) / 2 \quad (2)$$

where P_s is daily precipitation at the site, P_{B1} is daily precipitation input from the first (or only) base station, P_{B2} is daily precipitation input from the second base station, A_s is the long-term average annual precipitation at the site (from a precipitation map), and A_{B1} and A_{B2} are average annual precipitation from the first and second base stations.

APPENDIX G: EQUATIONS FOR CALCULATING HUMIDITY

The equations used to calculate day average relative humidity are based on dewpoint at the base station, which is corrected for elevation to the site, and day average temperature at the site calculated by MTCLIM using the equations given on page 4. The equations are based on Murray (1967) and are given by

$$SRH = (ES/ESD)*100$$

where *SRH* is day average site relative humidity in percent and *ES* is the saturation vapor pressure at dewpoint given by

$$ES = 6.1078*e^{(17.269*SDEW)/(237.3 + SDEW)}$$

and *ESD* is the saturation vapor pressure at the day average temperature given by

$$ESD = 6.1078*e^{(17.269*STEMP)/(237.3 + STEMP)}$$

STEMP is the day average temperature at the site calculated by MTCLIM and *SDEW* is the dewpoint at the site given by

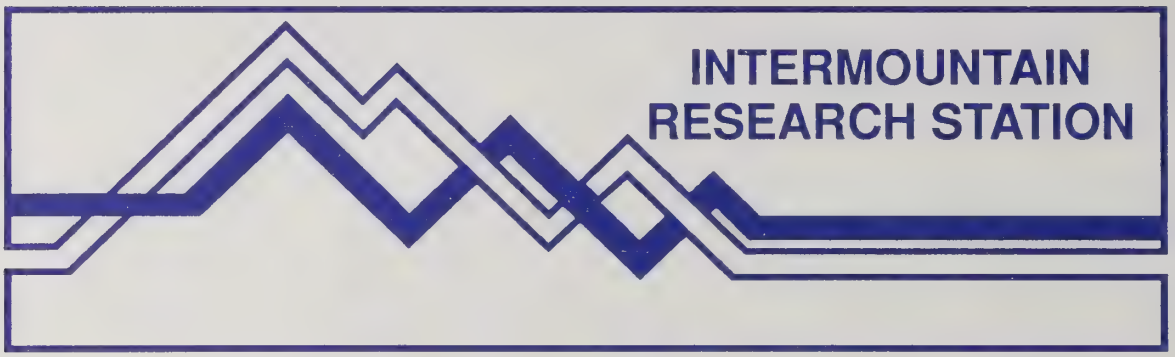
$$SDEW = BDEW - DLAPSE * (SELEV\text{-}BELEV)/1{,}000$$

where *BDEW* is the dewpoint at the base station, *DLAPSE* is the lapse rate for humidity (1.5 °F per 1,000 ft or 2.7 °C/1,000 m elevation), *SELEV* is the elevation in meters at the site, and *BELEV* is the elevation of the base station. When *BDEW* is not available or used the minimum temperature for the day is set equal to the dewpoint (appendix C).

Hungerford, Roger D.; Nemani, Ramakrishna R.; Running, Steven W.; Coughlan, Joseph C. 1989. MTCLIM: a mountain microclimate simulation model. Res. Pap. INT-414. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 52 p.

A model for calculating daily microclimate conditions in mountainous terrain is presented. Daily air temperature, shortwave radiation, relative humidity, and precipitation are extrapolated form data measured at National Weather Service stations. The model equations are given and the paper describes how to execute the model. Model outputs are compared with observed data from several mountain sites.

KEYWORDS: meterology, weather, climatology, temperature, solar radiation, humidity, precipitation, model



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Developmental Differences Among Five Lodgepole Pine Provenances Planted on a Subalpine Site in Montana

Dennis M. Cole

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ACKNOWLEDGMENTS

The author is grateful for the assistance of several individuals in initiating and conducting this study. David A. Perry, Oregon State University, collected, extracted, and stratified the seed. Frank Morby, nurseryman, Intermountain Region, Forest Service, supervised the growing and lifting of the seedlings used in the study. Lloyd Harris, Bozeman Ranger District, Gallatin National Forest, assisted in selecting the study site and planting the seedlings. Ward McCaughey, Bozeman Forestry Sciences Laboratory, has provided field assistance and consultation throughout the study.

RESEARCH SUMMARY

Developmental differences of progeny from lodgepole pine seed from British Columbia, Washington, Idaho, Utah, and a local population, were observed after 12 years in a provenance study conducted on a high-elevation site in southwestern Montana.

The short-term purpose of this study is to determine how these widely separated provenances of lodgepole pine differ in early expression of tree development and in variation of form among and between families. The long-range goal is to ascertain whether yield of lodgepole pine can be improved in this high-elevation Montana habitat by planting trees from distant populations that are cold acclimated but might differ in adaptation to length of growing season.

Seedlings from six to 10 families from each provenance were grown in the nursery to provide 3-0 stock for planting at the study site in the Gallatin National Forest in Montana. The study site is located at 6,600 ft (2,200 m) elevation, has a frost-free season of about 50 days, and receives about 30 inches (76 cm) of annual precipitation. From four to 10 offspring of each family were planted in consecutive planting spots in randomly allocated row plots. Distance between rows and trees within a row was 10 ft (approximately 3 m).

Mortality was recorded and total heights and lengths of terminal leaders of trees were measured in 1976, 1978, 1979, 1982, and 1987. Crown width was measured in 1982 and 1987. Diameter at breast height and heights to the lowest live limb, base of the balanced crown, and to the widest part of the crown were measured in 1987.

Survival was analyzed with chi-square procedures, and provenance differences in various growth characteristics were determined by analyses of covariance, using either initial height of seedlings at time of planting or the previous year's total height as covariates, where appropriate. Least-square means procedures were used to adjust for unequal numbers of families within provenances and seedlings within families. Probabilities of difference in least square means were used to determine statistical differences among the provenances in their various growth expressions and to compare provenances for relative degrees of among- and within-family variation.

Survival differences among the provenances after 12 years were found to be statistically nonsignificant at the 0.05 level, suggesting that any provenance differences in development of surviving trees that might occur would be likely to be influenced by other genetically controlled traits than by cold intolerance alone. After 12 years, trees of the Idaho provenance have become as large, or larger, than all other provenances in height, diameter, and crown width—and show the greatest degree of crown recession. The British Columbia and Washington provenances followed in magnitude of these developmental characteristics, but differences with the Idaho provenance were not statistically significant, except for the lower crown widths of the Washington provenance. The local Montana provenance was generally intermediate in all characteristics except crown recession, in which it had the least. The Utah provenance showed the least development in height, diameter, and crown widths, but had consistently the highest levels of within-family variation for all growth expressions measured. Patterns of among-family variation among the provenances differed from growth expression to growth expression, but overall the Washington population exhibited the most variation among families, and Montana the least.

The performance data and relative indicators of genetic variability developed in this study should be useful in selecting genotypes for improved yield performance in this and similar habitats. After 12 years of comparison, the Idaho provenance tested here appears to offer the greatest potential for timber management, but genotypes of other provenances might be selected to emphasize other traits, such as slower crown recession for retaining hiding and thermal cover longer in stands—an important consideration in wildlife management.

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Developmental Differences Among Five Lodgepole Pine Provenances Planted on a Subalpine Site in Montana

Dennis M. Cole

INTRODUCTION

Harvesting of lodgepole pine (*Pinus contorta* var. *latifolia*) is usually done by clearcutting and the harvested area is usually regenerated naturally from the local seed source. However, natural regeneration sometimes fails when site scarification is inadequate or when logging and silvicultural activities are not coordinated with the level of cone serotiny in the stand. In these cases, the site is usually planted using seedlings from a nearby seed source. Recent studies suggest, however, that improved growth and yield is possible from alternative seed sources, judiciously chosen.

Perry and Lotan (1978), in a greenhouse experiment, found that seedlings from Washington, Idaho, and British Columbia seed were taller and heavier than those from high-elevation seed from Montana and Utah, although differences in response to day-length and temperature were not significant. Illingworth (1975) found that early height growth and frost resistance differed among 144 lodgepole pine provenances planted at coastal and inland locations in British Columbia, and suggested that distant populations might be grown successfully in continental climes if sufficiently adapted to cold. Subsequent studies have clearly shown that adaptation in lodgepole pine is closely related to environmental variables (Critchfield 1980; Rehfeldt 1987; Rehfeldt and Wykoff 1981). Rehfeldt and Wykoff (1981) found that genetic differences in height growth, among 30 lodgepole pine populations from widely different elevations of Idaho and Montana, were expressed through adaptation of shoot elongation to the length of the growing season, rather than to the noticeably different temperatures alone. Correspondence of variation in shoot elongation with variation in freezing tolerance was interpreted as evidence that height growth of lodgepole pine populations is coordinated with cold acclimation through adaptation to the length of the growing season. More recently, Rehfeldt (1983, 1986, 1987) in a series of seedling studies has described the adaptation potential of Rocky Mountain lodgepole pine populations for cold hardiness, growth potential, and insect and disease resistance, and developed guidelines for determining seed transfer limits.

On the basis of the availability of wind-pollinate seedlings from the same parent trees used in Perry's greenhouse experiments, I decided in 1975 to evaluate long-term field performance of those geographically distinct populations when planted in a cold, high-elevation Montana environment representing a large area of the *Abies lasiocarpa* climax series where lodgepole pine is a dominant forest cover type. Early survival and growth differences among the five provenances were reported through the seventh growing season (Cole and McCaughey 1984). This paper reports sapling-stage development through 12 growing seasons and how different growth expressions vary among and within provenances and families.

STUDY DESCRIPTION

Study Site

The study site is located near Rat Lake—Squaw Creek drainage, Gallatin National Forest, Montana—in a clearcut area harvested in 1970. Lodgepole pine was the major species in the harvested stand, with a small proportion of Engelmann spruce (*Picea engelmannii* Parry) distributed throughout the area. Site index (base 100) for lodgepole pine is between 60 and 70 ft (18 and 21 m) and elevation is about 6,600 ft (2,000 m) above sea level. The ecological habitat type (Pfister and others 1977) is *Abies lasiocarpa/Linnea borealis*. Prominent understory species at the time of harvest were *Linnea borealis*, *Vaccinium caespitosum*, and *Calamagrostis canadensis*.

The soil in the study area is developed to 18+ inches (46+ cm) and is classified as a silt loam of the Cryochrepts-Cryoboralfs-Lithic Cryoborolls group of the Inceptisol-Alfisol association (USDA Soil Conservation Service 1978). The study area lies across a gentle draw midway on a gentle north-facing slope. The site is quite moist into July of most years. No weather data are available for the specific site, but annual precipitation is judged to be a few inches greater than the 30 inch (76 cm) average recorded at the Squaw Creek Ranger Station, located about 4 mi (6.4 km) down the drainage at about 1,200 ft (365 m) lower elevation. The average length of the freeze-free season is about 50 days (Caprio 1965).

Seedling Origin, Propagation, Planting

Seed was collected from 10 parent trees in each of five widely separated stands in Utah, Montana, Idaho, Washington, and British Columbia. Locations, latitudes, elevations, habitat types, and site indexes of the stands are shown in table 1. Stands were selected from similar ecological habitat types (Daubenmire and Daubenmire 1968) to represent, as much as possible, reasonably similar growing opportunities for lodgepole pine. In this regard, the effects of shorter and cooler growing seasons at the higher elevation Montana and Utah sites were assumed to be somewhat offset by greater growing season precipitation than commonly occurs at the Idaho, Washington, and British Columbia sites (Perry and Lotan 1978).

Seedlings were grown at the Lucky Peak Nursery near Boise, Idaho, and planted as 3-0 stock on the study site in the spring of 1975. Seedlings were lifted from the nursery before spring growth began in 1975, bundled by parent tree identity, and placed in cold storage until the study site was accessible.

On June 9-10, 1975, 284 seedlings, representing from four to 10 offspring of each mother tree, were planted in 13 rows of a 0.75-acre (0.3-ha) plot. Rows were spaced 10 ft (~3 m) apart and trees were spaced 10 ft (~3 m) apart in the rows. Planting spots were grouped by parent tree—that is, all seedlings from a given parent were planted in a row plot (consecutive planting spots in a row)—but the row-location of parent-groups was randomized. The planting could have been randomized to the individual-tree level, but this would have required unacceptable handling and delay in separating and randomizing the seedlings to that level—risking study confounding from planting effects. Therefore, seedlings were randomized only to the parent-group (family) level, planted, and identified by tagged stakes showing the provenance, parent tree, and individual tree numbers of each seedling.

Measurements and Analysis

Mortality was recorded, and total heights and terminal leader lengths were measured in centimeters—in 1976, 1978, 1979, 1982, and 1987. Codes were used to identify healthy versus unhealthy trees and those with damaged versus undamaged leaders. Crown width was added to the measurements in 1982 and 1987; and diameter at breast height and heights to the lowest live limb, base of the crown, and to the widest part of the crown, were measured in 1987.

Data were analyzed with the chi-square test for differences in survival and frequency of damaged or unhealthy trees, and by analysis of covariance for differences in growth between the provenances.

Although differences in the frequency of unhealthy and damaged trees among the provenances were highly insignificant, according to the chi-square test, only healthy, undamaged trees were included in the growth analyses.

The initial height of seedlings at the time of planting was used to adjust the provenance means of the various growth expressions. A covariance model of the form $Y = b_0 + b_1$ Provenance $+ b_2$ Initial Height was used to evaluate the influence of provenances on growth. The covariate, Initial Height, was found to be independent of provenances for all growth expressions; therefore, interaction effects between provenances and initial heights was not involved in the analysis. Another coveriance model of the form $Y = b_0 + b_1$ Parent $+ b_2$ Initial Height was used to evaluate the significance of variation in the various growth expressions due to parents (families) within provenances.

Although the overall F test for provenance means in the analysis of covariance was not particularly significant for some growth expressions in 1987, pairwise comparisons can be made to test partial null hypotheses in which some means are equal but others differ (SAS Institute 1985).

Table 1—Location and site characteristics of stands providing seed for provenance study

Stand	Location	Elevation		Habitat type	Site index (Alexander 1966)
		Ft	*m*		
Washington	Sherman Pass, Colville N.F., lat. 48°36' N.	5,250	(1,600)	*Abies lasiocarpa - Pachistima myrsinites* (Daubenmire and Daubenmire 1968)	90
Montana	Butte Meadows, Gallatin N.F., lat. 45°26' N.	7,220	(2,200)	*Abies lasiocarpa - Galium triflorum* (Pfister and others 1977)	80
Utah	Gilbert Creek, Wasatch N.F., lat. 40°54' N.	8,200-9,150	(2,500-2,790)	*Abies lasiocarpa/Berberis repens* and *Abies lasiocarpa/Vaccinium scoparium* (Pfister 1972)	45
Idaho	Little Slate Cr. Nez Perce N.F., lat. 45°40' N.	5,100	(1,550)	*Abies grandis - Xerophyllum tenax* (Steele and others 1981)	90
British Columbia	Caribou Land District, lat. 53°25' N.	2,300	(700)	Unknown, but probably *Abies lasiocarpa/Clintonia uniflora* (Daubenmire and Daubenmire 1968)	100

Accordingly, the least squares means (LSMEANS) method, with the probability of difference (PDIFF) option, of the General Linear Models (GLM) procedure of the SAS statistical program (SAS Institute 1985) was used to evaluate variation in the various growth expressions, among and within families and provenances. The SAS procedures provide methodologies for dealing with the unbalanced design of this study that were not before available and furnish a common basis for evaluating changes in the development of provenances between 1982 and 1987. Some of the 1982 measurements that were reported earlier (Cole and McCaughey 1984) were also reanalyzed with the SAS statistical program; however, interpretations were not changed by the reanalysis.

To evaluate among-family variation in tree development, I used p-values from the SAS General Linear Models PDIFF option described above and determined the proportion of possible family differences for each growth expression and provenance that had a 10 percent or less probability of occurring by chance. These proportions provided a relative means to compare provenances for extent of among-family variation in the various growth expressions measured.

Within-family variation was assessed by computing coefficients of variation for growth expression standard deviations (Steel and Torrie 1960) and comparing their relative magnitudes among provenances.

RESULTS AND DISCUSSION

Variation Among Provenances

Perry (1974) in his greenhouse study of the same wind-pollinated families tested in this provenance study found that British Columbia seedlings were consistently taller, Idaho and Washington were intermediate, and Utah and Montana formed a lower group—except under the two shortest day lengths where Utah and Montana trees were taller. With respect to growing period, there were significant differences among the provenances in reaction to day length, but not temperature. The significance of the day length-provenance interaction, however, was due primarily to the British Columbia seedlings, which when removed from the analysis resulted in a nonsignificant effect of day length on the other provenances. In the following sections, differences in survival, condition, and development of the provenances 12 years after planting, are discussed.

SURVIVAL AND TREE CONDITION

Mortality continues, but to a lesser degree and with less difference between provenances than observed earlier (table 2). A chi-square test of survival among the provenances through 1987 indicates that survival differences of the magnitude of table 2 would occur by chance about 70 percent of the time; therefore, survival among provenances after 12 years is not considered to be statistically significant. Similarly, a chi-square test of numbers of damaged and healthy trees in each provenance in 1987 indicated that such provenance differences would occur by chance about 87 percent of the time. Therefore, it appears that mortality to date has occurred randomly throughout the study area and has not been due to any particular factor. The varied mortality history of the study to date suggests that developmental differences between the provenances might also be significantly influenced by other traits in addition to cold acclimation.

Table 2—Number of trees planted and percentage of trees surviving in 1976, 1982, and 1987 by provenance

Provenance	No. trees planted 1975	Percent surviving 1976	1982	1987
Utah	63	90	83	81
Montana	51	90	88	82
Washington	46	87	78	76
Idaho	43	77	74	72
British Columbia	81	88	84	81
Total and percentage means	284	86	81	79

TREE DEVELOPMENT

Means of tree development measures for each provenance and year of measurement are summarized in table 3. Results of covariance analyses for evaluating provenance differences in early development are discussed immediately below, while evaluations of the relative variation among and within families and provenances, are discussed further along.

Height Growth—Total tree height increased markedly from 1982 to 1987 in all provenances (table 3); however, the significance of the overall F test for provenance differences in adjusted sapling heights declined appreciably (p values for the F test were 0.01 and 0.29, respectively). Nonetheless, pairwise comparisons of adjusted provenance means were made to determine if any provenances differed ($p < 0.10$) in heights in 1987. Least-squares means of heights in 1987 (H87) were estimated to account for unequal numbers of trees among the provenances, and used to test specific provenance differences in total height in 1987. In these comparisons, Idaho trees were significantly taller than Utah trees in 1987 ($p = 0.03$). No other differences were practically significant (p values > 0.20).

The greatest absolute height growth was previously in British Columbia trees; however, their annual percentage rate of height growth since 1982 has fallen behind all other provenances, and the Idaho trees are now virtually equal in total height with the British Columbia trees (table 3). In addition, although Idaho trees are still significantly taller than Utah trees, the height growth rate of Utah trees in the last 5 years has been greater (table 3). These results suggest that the patterns of height growth rates and attained heights among the provenances might be considerably different in the future.

Crown Width—Absolute crown widths were greatest in Idaho and British Columbia trees (table 3); but since crown width is strongly correlated with tree height, 1987 crown widths (CW87) were covariance adjusted for

Table 3—Periodic annual height growth percent, and means of: total heights, terminal leader lengths, heights to lowest limb, heights to crown base, crown widths, and diameters at breast height (d.b.h.)—by provenance and year of measurement

Provenance	Year	Height growth	Total height	Terminal leader length	Height, lowest limb	Height, crown base	Crown width	D.b.h.
		Percent			*Centimeters*			
Utah	1975	—	13.5	—	—	—	—	—
	1976	40.0	18.9	5.4	—	—	—	—
	1978	41.3	34.5	10.9	—	—	—	—
	1979	30.7	45.1	12.1	—	—	—	—
	1982	31.3	87.5	19.2	—	—	46.1	—
	1987	31.6	225.9	39.8	23.7	34.0	97.1	3.1
Montana	1975	—	13.0	—	—	—	—	—
	1976	43.8	18.7	5.7	—	—	—	—
	1978	48.4	36.8	11.0	—	—	—	—
	1979	31.5	48.4	12.9	—	—	—	—
	1982	46.9	93.8	21.5	—	—	53.3	—
	1987	32.4	245.6	38.8	20.7	32.3	105.5	3.6
Washington	1975	—	16.1	—	—	—	—	—
	1976	42.9	23.0	6.9	—	—	—	—
	1978	44.8	43.6	13.4	—	—	—	—
	1979	29.8	56.6	13.8	—	—	—	—
	1982	29.3	110.8	20.8	—	—	53.6	—
	1987	28.0	268.1	47.1	26.4	38.8	104.0	3.7
Idaho	1975	—	14.8	—	—	—	—	—
	1976	43.9	21.3	6.5	—	—	—	—
	1978	52.6	43.7	15.5	—	—	—	—
	1979	37.8	60.2	15.9	—	—	—	—
	1982	32.3	119.2	24.4	—	—	62.2	—
	1987	25.7	277.1	45.2	27.8	42.4	124.1	4.0
British Columbia	1975	—	19.4	—	—	—	—	—
	1976	40.2	27.2	7.8	—	—	—	—
	1978	52.5	56.0	17.6	—	—	—	—
	1979	29.5	72.5	18.3	—	—	—	—
	1982	28.0	133.4	24.4	—	—	69.7	—
	1987	21.6	277.5	42.4	23.2	37.4	121.5	3.8

current height (H87) to make provenance comparisons. The F test indicated highly significant differences in 1987 crown widths among the provenances, when adjusted to a common height in 1987 ($p = 0.0002$). According to pairwise comparisons of least-squares means, Idaho and British Columbia crown widths in 1987 were significantly greater for a given height than those of Montana, Utah, and Washington; while Montana was significantly greater than Washington (p values < 0.07—p values of all other comparisons > 0.22). This pattern of differences is appreciably different than in 1982, when crown widths for a given height were significantly greater for Montana and British Columbia trees than those of Utah (p values < 0.05).

Crown Recession—Heights to the lowest live limb (HLL87) and the base of the balanced live crown (HBC87) were measured in 1987 as indicators of crown recession and found to vary appreciably among provenances. The Montana population had the least recession in both lowest live limb and base of the balanced crown, British Columbia and Utah were intermediate, while the Idaho and Washington populations had the most (table 3). After covariance adjustment for initial height of seedlings when planted, variation due to provenances was found to be highly significant for both variables ($p = 0.01$ and 0.001, respectively), according to the F statistic. Pairwise comparisons of least-squares means indicate that differences between Montana versus Idaho and Washington trees were statistically very significant (p values ≤ 0.01). Several other provenance comparisons showed statistically significant, though lesser, differences.

Like Montana, Utah and British Columbia trees had markedly lower live limbs than Idaho trees ($p = 0.05$ and 0.02, respectively), but the only other difference in height of lowest live limb to approach those levels of significance was that between British Columbia and Washington trees ($p = 0.10$).

In heights of balanced live crowns (HBC87), the Montana population also showed significantly less recession than British Columbia ($p = 0.07$), as well as Idaho and Washington (as mentioned above). The Utah population also showed significantly less crown recession than Idaho and Washington trees (p values < 0.08), but were not greatly different than British Columbia trees in this regard ($p = 0.34$). The British Columbia trees were intermediate, in crown recession—and, although significantly greater than Montana trees, were significantly less ($p = 0.01$) than those of Idaho.

These provenance differences suggest that early crown recession is under genetic influence. Further evidence is provided in the discussion of tree development variation within provenances presented below.

Stem Diameter—Breast height (4.5 ft [1.37 m]) diameter (D87) of saplings was measured for the first time in 1987, when all but two surviving trees in the study had attained that height. Idaho saplings were the largest in absolute diameter in 1987, while Utah saplings were the smallest (table 3). British Columbia, Washington, and Montana saplings ranked behind Idaho in that order; however, when adjusted for initial seedling heights, stem diameters in 1987 showed a somewhat different pattern of differences in least-squares means than seen in table 3 for unadjusted means. Specifically, British Columbia and Montana switched places from the order shown in table 3. Statistically, comparisons of least-squares means showed that adjusted Idaho diameters were significantly larger than those of British Columbia and Utah, while Montana diameters were significantly larger than those of Utah saplings (p values < 0.10).

Variation Within Provenances

Perry (1974) found that wind-pollinated siblings of the families tested in this provenance study had a mixed pattern of variation among and within families, in response to day length. British Columbia seedlings had more variation within families than among them, while the opposite was true for Utah seedlings. Washington and Idaho seedlings had considerable variation both within and among families, while those from Montana seemed to have the least of both types of variation.

In this study, among-family differences in sapling development were evaluated by comparing, for various growth expressions, the proportions of possible family differences within-provenance that had p values ≤ 0.10 (table 4). Considering all growth expressions together (see last column, table 4), Montana saplings had much less variation among families, while Washington and Utah had the most. Because Utah seed was collected over a 850-ft (290-m) elevational range (table 1), variation among families would be expected to be greater than within families, as the likelihood of different ecotypes among the parent trees increased. But Washington seed was collected within a 10- to 25-acre (5- to 10-ha) area at the same elevation, so its among-family variation appears to be more a result of genetic variation. British Columbia saplings showed moderately low variation among families for all growth expressions. Idaho was generally intermediate among the provenances, except it showed relatively high among-family variation for height growth measures while showing the least in the crown recession variables HBC87 and HLL87. In contrast, the Utah saplings showed more variation among families in these two crown recession indicators than the other provenances combined—again, probably due to the wide elevational spread among the parent trees.

Table 4—Percentages of family differences, in least-squares means, having less than a 10 percent probability of occurring by chance

Provenance	Characteristic[1]							Average percent of family difference
	H87	L87	PHG	HLL	HBC	CW87	D87	
	Percent							
Washington	57	48	57	14	0	52	33	37.3
Montana	5	0	0	10	0	0	10	3.6
Utah	47	31	53	47	44	42	33	42.4
Idaho	47	47	27	0	0	20	7	21.1
British Columbia	13	18	16	4	18	20	11	14.3

[1] H87 = total height in 1987
L87 = leader length in 1987
PHG = periodic height growth in 1982-87
HLL = height to lowest live limb
HBC = height to base of balanced crown
CW87 = crown width in 1987
D87 = diameter at breast height in 1987.

Table 5—Coefficients of variation (CV) for within-family standard deviations of characteristics, by provenance

Provenance	Characteristic[1]							Average CV
	H87	L87	PHG	HLL	HBC	CW87	D87	
Washington	50	49	43	28	39	26	81	45
Montana	32	41	34	29	40	30	20	32
Utah	47	48	44	51	43	70	50	50
Idaho	23	40	38	18	26	32	24	29
British Columbia	47	29	42	36	36	26	36	36

[1] H87 = total height in 1987
L87 = leader length in 1987
PHG = periodic height growth in 1982-87
HLL = height to lowest live limb in 1987
HBC = height to base of balanced crown in 1987
CW87 = crown width in 1987
D87 = diameter at breast height in 1987.

Within-family variation was evaluated for each provenance and growth expression by determining the coefficients of variation for standard deviations of families (table 5). No particular pattern of relative within-family variation among the provenances in individual growth expressions is evident in table 5, except for Utah, which had consistently high levels of within-family variation for all growth expressions. Unlike among-family variation, within-family variation of the Utah provenance would not be so likely to be affected by elevational differences among the parent trees. To assess relative degrees of within-family variation among provenances, all growth expressions were combined (see last column, table 5). On this basis, Utah saplings had distinctly greater variation within families than the other provenances, while Idaho and Montana had the least.

CONCLUSIONS AND MANAGEMENT IMPLICATIONS

After 12 years, earlier differences in survival and tree condition among the provenances have become statistically insignificant. Significant differences between provenances were found; however, for several developmental traits, as well as indications of differences between the provenances in among- and within-family variation.

Height growth differences among the provenances are declining, largely due to the slowest growing provenances beginning to catch up with the taller provenances. Only the tallest (Idaho) and the shortest (Utah) provenances were significantly different at year 12.

The pattern of height-adjusted crown width among provenances has changed considerably from year 7 to 12, with the previously widest Montana population dropping to intermediate position. Genetic differences in the crown width trait among lodgepole pine populations are highly correlated with those of tree height (Rehfeldt 1985); therefore, provenance means for crown width were evaluated with height held constant. The tallest provenances (Idaho and British Columbia) still had significantly greater crown widths for a given height than the Montana, Utah, and Washington provenances (p values < 0.07).

Crown recession differences among provenances were assessed for the first time at year 12, using measurements to the lowest live limb and to the base of the balanced live crown. Differences in provenance means were adjusted for seedling height when planted and found to be highly significant ($p < 0.01$) for both indicators of crown recession. The Montana provenance had the least recession in lowest live limb and base of the balanced live crown, while the Idaho and Washington provenances had the most. Utah and British Columbia trees were intermediate in crown recession. The height of the lowest live limb and the general recession of crowns in sapling stands of lodgepole pine are of more than passing interest to field foresters. Early thinnings for stocking control are sometimes ineffective, due to branch turnups, when lower live limbs or viable branch buds exist below the stump height that can be practically attained in thinning. In most areas, foresters have determined by experience the minimum stand age and practical stump height for avoiding the branch-turnup problem; however, if the persistence of the lowest live limb is under genetic influence as suggested by these results, it should be considered in tree improvement and planting programs. Likewise, crown recession has become increasingly important in relation to hiding and thermal cover for wildlife, and should be considered in seed transfer decisions.

Stem diameters were measured at breast height (4.5 ft [1.37 m]) for the first time at year 12 and, when adjusted for seedling height when planted, were found to vary significantly among the provenances. Diameters of Idaho trees were significantly greater than those of British Columbia and Utah, while Montana trees were significantly larger than those of Utah (p values < 0.10). Washington trees were intermediate in breast height diameter, but were not significantly different than the other provenances.

Because the provenances studied here represent widely separated geographic locations and a considerable range of elevations, we expected appreciable differences (as were noted) in the means of most traits measured in this study. Rehfeldt and Wykoff (1981) found that growth differences among Montana and Idaho lodgepole pine populations

were more a result of adaptation to length of growing season than to growing season temperature alone. Further, Rehfeldt (1986) developed methods for separating the relative influences of elevation and geography on various heritable traits of lodgepole pine in eastern Idaho and western Wyoming. From these he estimated that elevation accounted for over 70 percent of the variance in five shoot-elongation variables, while geography accounted for less than one-third of the variance. A conclusion drawn in both of these studies (Rehfeldt 1986; Rehfeldt and Wykoff 1981) is that successful transfer of lodgepole pine populations from their origins is largely a matter of balancing the traits of nondormant cold hardiness and capacity for late growth (shoot elongation after the fourth week); and that these traits are considerably more influenced by elevation than by geography. In this vein, populations from lower elevations were found to have considerably greater capacity for late growth than high elevation populations, but this made their seasonal growth more vulnerable to late-growing-season frosts.

Referencing the elevation and geographical location of the study plantation to elevational and geographical differences of the five provenances reported in this study (table 1), we would expect that the low-elevation (2,300-ft [700-m]) British Columbia seed source would have the greatest growth capacity, but be more vulnerable to growth attrition due to cold damage. Observance of some decline in performance of the British Columbia provenance from age 7 to age 12, relative to other provenances, suggests that this is the case, and as the trees have now grown beyond the snow level, maladaptation to this cold site is offsetting the earlier growth advantage of the British Columbia provenance. At the other elevation extreme, the Utah provenance would be expected to be relatively limited in its growth capacity on the lower elevation Montana test site, as was observed. The elevationally intermediate Idaho and Washington provenances, although of essentially the same elevation, have developed somewhat differently in this study. Generally, the Idaho trees have become as large, or larger, than all other provenances in height, diameter, and crown width—and show the greatest degree of crown recession. The Washington trees have developed less than the Idaho trees in all traits measured, but with the exception of crown width, the differences are not statistically significant. Trees from the local Montana seed source exhibited intermediate development in relation to the other provenances, except for crown recession in which Montana trees exhibited the least change.

The provenances tested here differed in among- and within-family variation. The Montana families showed the least and Washington the most among-family variation, of the four provenances where seed was collected from a restricted area and elevation. The Utah provenance could not be compared in this regard because families were collected from an elevational range of nearly 1,000 ft (290 m); thus, a large amount of the among-family variation was attributed to elevational differences. The pattern of within-family variation among provenances differed from trait to trait in this study, with the exception of the Utah trees which exhibited consistently the highest within-family variation. Because variation within family is not as likely as among-family variation to be influenced by elevation, this suggests that lower latitude-higher elevation lodgepole pine populations, such as in Utah, might possess greater within-family variation than more-northerly populations. This, as well as some of the other questions raised by this study, will perhaps be answered by long-term lodgepole pine provenance trials (involving more populations from each provenance than this study) that are now established throughout the Northern Rockies.

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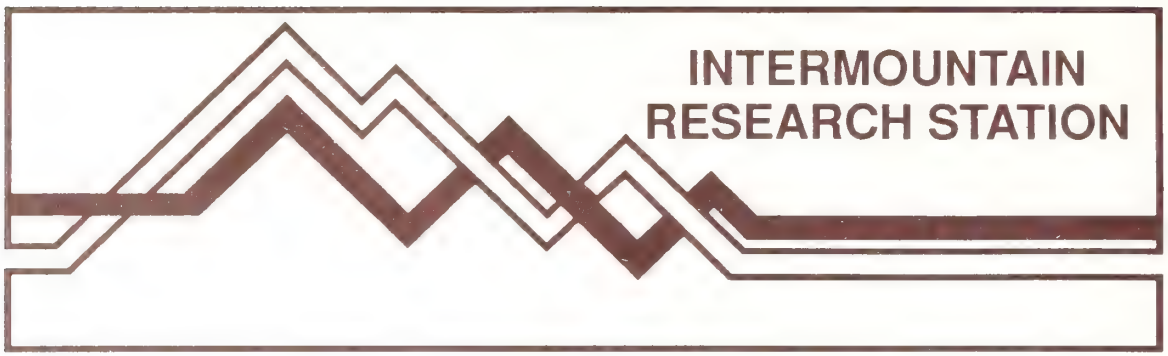
Survival and development of progeny from lodgepole pine seed from British Columbia, Washington, Idaho, Utah, and a local population were observed after 12 years in a provenance trial conducted on a high-elevation site in southwestern Montana. Differences among provenances were not significant for survival, but were significant for developmental traits. The Idaho provenance showed the greatest growth, the Utah provenance the least. Among-family variation was greatest in the Washington provenance; within-family variation was greatest in the Utah provenance.

KEYWORDS: progeny testing, seed transfer, *Pinus contorta*



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Research Paper
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Susceptibility of Ponderosa Pine to Western Gall Rust Within the Middle Columbia River System

R. J. Hoff

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THE AUTHOR

R. J. HOFF is principal plant geneticist with the Intermountain Research Station's Forestry Sciences Laboratory in Moscow, ID. He received a B.A. degree in biology from Western Washington State University and a Ph.D. in botany from Washington State University.

RESEARCH SUMMARY

Ponderosa pine from the middle Columbia River system proved to be highly resistant to western gall rust. Only 28 percent of the seedlings that were inoculated at the beginning of their second growth year were infected 39 months after artificial inoculation. Three major resistant reactions were observed: trees that expressed no symptoms, trees that had visible bark reactions, and trees in which the fungus causing the initial infection later died.

The degree of infection increased with elevation, with 15 percent of the variation accounted for. A stepwise multiple regression used a combination of elevation, azimuth, distance from inoculum source, and southwest departure to account for 26 percent of the variation. This analysis also indicated that the populations that were nearest to the inoculum source were most susceptible.

My conclusions were: (1) Most of the variation in susceptibility to western gall rust was random. (2) There was a moderate association with elevation and geographic area. (3) Three distinct resistance reactions were operating.

This information should be useful to forest managers in selecting stands for collecting seed and for selecting superior seed trees for reforestation and tree improvement.

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Susceptibility of Ponderosa Pine to Western Gall Rust Within the Middle Columbia River System

R. J. Hoff

INTRODUCTION

Western gall rust caused by *Endocronartium harknessii* is a relatively minor disease of northern populations of ponderosa pine (*Pinus ponderosa* var. *ponderosa*). Most damage is to young trees and galls are frequently confined to branches (Leaphart 1955; Peterson 1959).

Thomas and others (1984) reported that ponderosa pine from Idaho, eastern Washington and Oregon, and central and western Montana were most resistant, and that populations from the Colorado plains and the Southern Rockies were most susceptible to gall rust. A more detailed study of central Idaho populations, using artificial inoculation with high spore density, revealed many highly susceptible populations (Hoff 1986). Infection among populations ranged from 65 to 95 percent.

The purpose of this paper was to assess variation patterns in susceptibility to western gall rust in populations of ponderosa pine from northeastern Washington, northern Idaho, and western Montana.

MATERIALS AND METHODS

Seeds from 125 populations from northeastern Washington, northern Idaho, and Montana west of the Continental Divide, and covering the elevation range of the species, were included in this test (fig. 1). Most stands were represented by an equal volume of seed from 10 randomly chosen trees. Some collections were from several squirrel caches. Diversity was assured in the squirrel cache collections by selecting cones with a variety of morphologies, sizes, and colors. The seeds were sown in containers (8 in^3) and grown and overwintered in a shadehouse at the Forestry Sciences Laboratory at Moscow, ID (lat. 46°44' N., long. 1170°0'W., elevation 2,650 ft). The seedlings were watered and lightly fertilized, with the objective of producing seedlings that were not stressed but without accelerating their growth.

The experimental design was: 125 populations, 10 seedlings per population per replication, three replications. Seedlings were grown in row plots. Total seedlings were 1,250 per replication and 3,750 for the test.

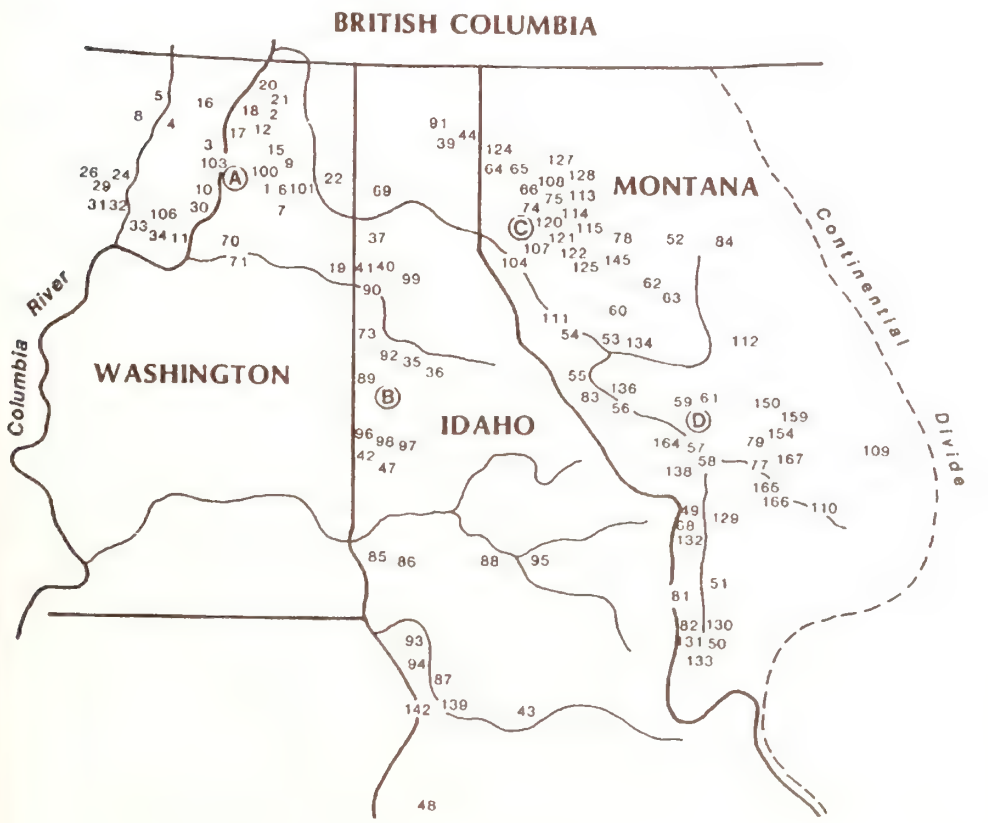

Figure 1—Number and locations of populations of ponderosa pine stands that were included in this test. Letters A to D locate elevation clines presented in figure 4.

In May the seedlings were moved into a mist chamber in preparation for inoculation. The seedlings were just beginning their second growing season, and needles were just beginning to break out of the fascicle sheaths. Mist nozzles were operated to provide a constant visible fog throughout the chamber. Twenty-four hours later, the stems of the seedlings were wet and allowed to sit for 1 hour to let excess moisture drain. The seedlings were then inoculated.

Fresh inoculum was collected from at least 50 galls from a young ponderosa pine stand located at the Lone Mountain Tree Improvement site (lat. 47°54' N., 116°49' W., elevation 2,488 ft) about 25 miles north of Coeur d'Alene, ID. Inoculation was accomplished on May 30, 1984, by blowing spores over the seedlings using an air-sprayer adapted from an Erlenmeyer flask. Each replication was inoculated separately with a mixture of 1.2g of aeciospores and 7g of talc. This gave a spore-to-seedling ratio of about 20,000 to 1. The seedlings were kept in the mist chamber for an additional 72 hours making sure that a visible fog was maintained. The mist nozzles were then turned off and the seedlings allowed to slowly dry. When dry, they were moved to a shadehouse. After a couple of weeks of acclimation, they were moved to a nursery at Priest River Experimental Forest (lat. 48°21' N., long. 116°52' W., elevation 2,400 ft), where they were planted at a 6- by 6-inch spacing in beds 30 ft wide. The 10 seedlings for each provenance in each replication were planted in two adjacent rows of five trees each. Planting dates were June 19 and 20, 1984.

Inspections for symptoms of infection were made for each seedling at 3 months, 15 months, 27 months, and 39 months after inoculation. Data were tallied for the presence of galls and reactions on the stem indicative of defense reactions. The following variables were used to assess variation among populations:

1. Infected. Trees with galls at 39 months.
2. Resistance. Trees with no galls at 39 months. These were placed into three categories of resistance:
   a. No reactions. Trees that did not have galls or bark reactions.
   b. Bark reactions. Trees that did not have galls but had visible reactions on the stem indicative of defense reactions.
   c. Gall death. Trees that had galls at 3, 15, or 27 months after inoculation for which the gall was dead at 39 months.
3. Rate of gall appearance. Percentage of trees with galls at 39 months that were visible at 3 months.
4. Rust-killed trees. Trees with galls that died by 39 months.

Analysis of variance was used for each variable to determine significant differences among stands. Simple correlations were performed for the rust variables with 3-year-old height, needle length, percentage dead due to drought, and initiation of bud growth in a greenhouse. The growth and drought data were from Rehfeldt (1986) from different seedlings but from the same populations and same seed collection.

Simple and multiple regression models were used to relate the rust variables to elevation and geographic location of the seed source. The independent variables were elevation, latitude, longitude, northwest departure, southwest departure, azimuth from the inoculum source, and distance from the inoculum source. Northwest (latitude x longitude) and southwest (1/latitude x longitude) departures were derived by rotation of the grid of latitude and longitude by 45 degrees. Multiple regression was used when simple regression analysis of the rust variables were significant. Squares of the above independent variables were added to accommodate the possibility of nonlinear patterns of variation. Therefore, 14 independent variables were included in a stepwise regression for maximizing R^2 (SAS 1982). In addition, the geographic variables were nested within four geographic regions: northeastern Washington, most of Idaho, northwestern Montana including the most northerly stands in Idaho, and middle to southwestern Montana (fig. 1).

RESULTS

The analyses detected differences among populations for the degree of infection and in the kinds of resistance reactions (table 1). Most rust factors varied randomly with the environment; the degree of infection was the only factor that was related to elevation or geographic origin of the seed.

The average level of trees with galls 39 months after inoculation was 28 percent; populations varied from 3 to 63 percent (table 1 and fig. 2). Three major categories of resistance were evident: (1) trees that expressed no symptoms—38 percent; (2) trees that expressed bark reactions—52 percent; and (3) trees in which the galls died—10 percent. Differences among populations for rate of gall appearance and for death due to rust were high but not significant.

There were no strong associations between the rust factors and the environmental factors (table 2). The R^2 for level of susceptibility and elevation was 0.15, the highest single association. Using all environmental factors with the level of infection, the R^2 for the best fit stepwise multiple regression model was 0.26. Figure 3 shows geographic lines at a constant elevation (average elevation for all stands). The distance between contour lines equals $\frac{1}{2}[lsd(0.2)]$. Thus distance equivalent to two contour lines differs by a probability of about 0.2. When comparing populations from the same elevation, populations from the west central area—the area near the origin of the rust inoculum—displayed the highest level of infection. From here, the level of infection decreased in all directions.

Figure 4 shows the association between elevation of the seed source and the level of infection. The elevation clines are keyed to the four geographic areas shown to figure 1. And they all indicate that the degree of infection increases as elevation of seed source increases, although the relationship tails off at high elevation.

Table 1—Means, range, and analyses of variance of symptoms of infection among provenances of ponderosa pine 39 months after artificial inoculation with rust

Symptom of infection	Analysis of variance					
	$\bar{x}$	Range	df	MS	F	PR>F
	-- *Percent* --		*No.*	*Percent*		
Infection (trees with galls)	28	3-63	124	[1]0.090	2.11	0.0001
Resistant (trees without galls)	72	37-97	124	[1].102	2.04	.0001
Categories of resistance:						
No galls or bark reactions[2]	38	8-76	124	[1].110	1.42	.0106
Bark reactions only[2]	52	13-89	124	[1].093	1.30	.0446
Gall death[2]	10	0-36	124	[3].008	1.35	.0230
Trees with galls or bark reactions	72	28-93	124	[1].102	1.51	.0035
Rate of gall appearance[4]	35	0-78	124	[1].291	1.11	.2438
Rust-killed trees[5]	8	0-44	124	[3].012	1.00	.4955

[1]Transformed to arcsin $\sqrt{x}$.

[2]Percentage resistance category is of total resistance.

[3]Transformed to $\sqrt{x + 0.5}$.

[4]Rate of appearance determined by number of galls 3 months after inoculation/by number galls 39 months after inoculation.

[5]Data from galled trees only.

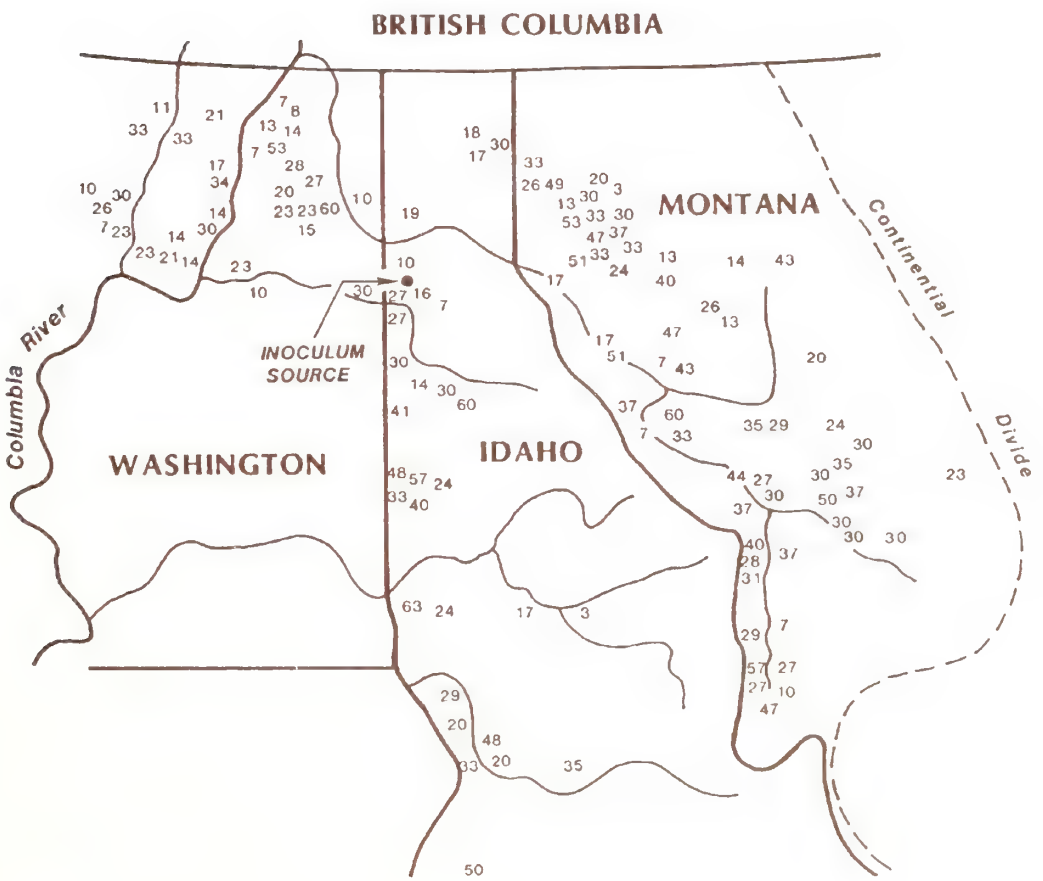

Figure 2—Level of infection of populations of ponderosa pine to gall rust. Numbers represent actual percentage of trees with galls for each population.

Table 2—R^2s between rust factors and various environmental factors[1]

Symptom of infection	Environmental factors						
	El	Lat	Long	NW	SW	AZ	Dist
Infection	0.15**	0.08**	0.05**	0.09**	0.02	0.05**	0.02
Resistant	.15**	.08**	.05**	.09**	.02	.06**	.02
Categories of resistance:							
No galls or bark reactions	0	0	0	0	0	0	0
Bark reactions only	.01	.02	.01	.02	.01	.01	0
Gall death	.01	.02	.02	.02	0	.02	.01
Trees with galls or bark reactions	0	0	0	0	0	0	0
Rate of gall appearance	0	0	.02	.01	0	.01	0
Rust-killed trees	0	.01	0	0	.02	0	0

**Significantly different at 1 percent.
[1]El = elevation, Lat = latitude, Long = longitude, NW = northwest departure, SW = southwest departure, Az = azimuth, Dist = distance from the inoculum source in miles.

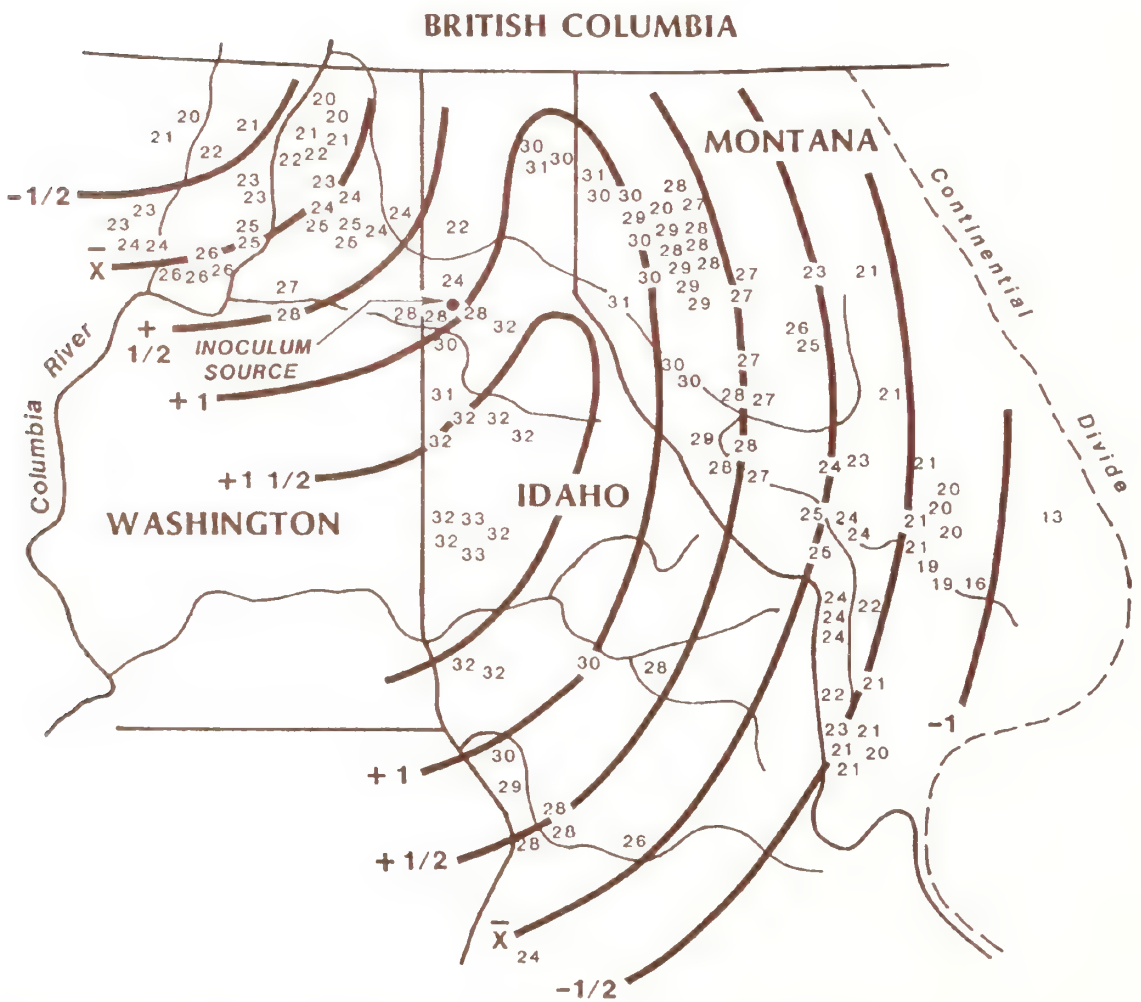

Figure 3—Level of infection of populations of ponderosa pine to gall rust. Numbers represent predicted percentage at the mean elevation of all populations (3,525 ft). Contour lines represent lines of equal performance. The interval between contour lines equals $^1/_2[lsd(0.2)]$ and lines represent positive or negative deviations from the mean value of all populations.

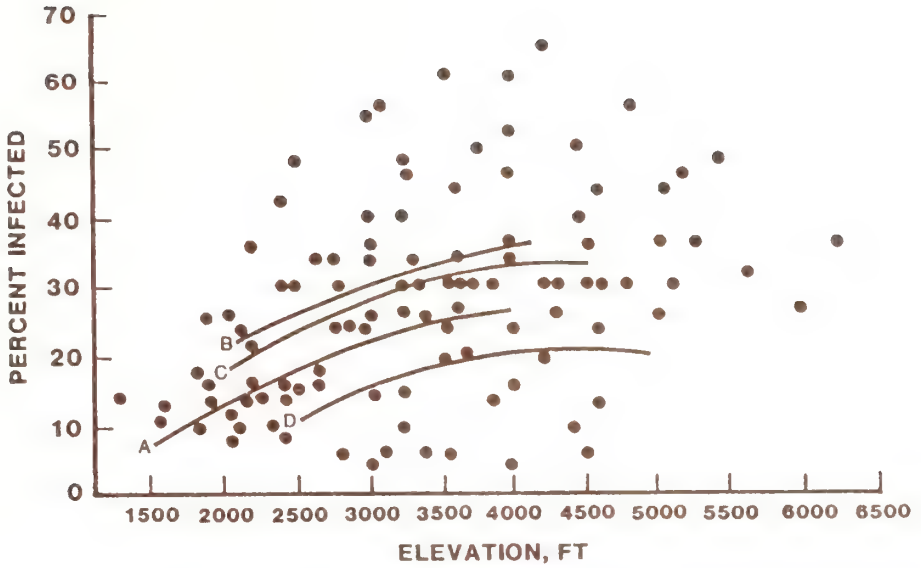

Figure 4—Actual percentage infection plotted against elevations. Lines A to D represent elevation clines for the geographic areas indicated in figure 1.

Table 3—Simple correlations among population means for rust data and growth data

Symptom of infection	Three-year height[1]	Leaf length[2]	Percent dead[3]	Elong[4]	Start[5]
Infection	–0.19*	0.10	0.12	–0.11	–0.07
Resistant	.19*	–.10	.12	.11	.07
Categories of resistance:					
No galls or bark reaction	.03	–.03	.24**	–.16	.03
Bark reactions only	.01	–.09	–.16	.14	–.02
Gall death	.04	.21*	.17	.03	–.01
Trees with galls or bark reactions	–.03	.07	–.25**	.07	.01
Rate of gall appearance	.06	.15	0	.05	–.17
Rust–killed trees	.06	.19*	–.05	.14	.04

*Significant at the 5 percent level of probability.
**Significant at the 1 percent level of probability.
[1]3-year height = height in the field (Rehfeldt 1986).
[2]Leaf length = length of leaf in the field (Rehfeldt 1986).
[3]Percent dead = trees that died in a drought test (Rehfeldt 1986).
[4]Elong = elongation of second year's growth in a greenhouse (Rehfeldt 1986).
[5]Start = initiation of growth in a greenhouse = time to reach 2 mm (Rehfeldt 1986).

Correlations of the rust data and growth characters were all very low and most of them were nonsignificant (table 3). The degree of infection was negatively correlated with 3-year-old growth; gall death and rust-killed trees were correlated with leaf length; and presence of galls or bark reactions were negatively correlated with percentage dead due to drought.

DISCUSSION

The general level of resistance of this collection of ponderosa pine populations to western gall rust was high; nonetheless, there were several populations that were highly susceptible. Three resistance categories were recognized. The first category of resistance was expressed as trees that had no symptoms. Such trees had either escaped inoculation or had defense mechanisms that prevented the fungus from penetrating the cuticle or cell walls of the epidermis or that confined the infection after penetration, so as to not be easily visible. The second category of resistance comprised trees with easily visible stem reactions. Whatever caused these reactions, possibly chemicals toxic to both host and fungus cells, resulted in the death of the fungus. The third category of resistance was expressed as typical galls at one of the first three inspections, but that were dead at the fourth inspection. This condition was signaled by a patch of necrotic tissue surrounding and encompassing the gall.

These three kinds of reactions were similar to those described by Hoff (1986). They also appear to be of the same type reported by Allen and others (1988) for resistance in lodgepole pine to western gall rust. Two other resistance reactions, namely rate of gall appearance and variation of rust-killed trees, were highly variable among provenances but were not statistically different.

Much of the variation among populations appeared to be random. But, for the degree of infection, variation among populations could be partly explained by geography. The R^2 for elevation was 0.15. Generally, as elevation of populations increased so did the level of infection; however, the relationship was curvilinear, with the level of infection leveling off at about 4,000 feet. That low-elevation sources are less susceptible is not surprising because weather conditions appear to be ideal for infection, with the probable result of more intense selection for resistance.

The multiregression that gave the best fit was a combination of elevation, azimuth, distance from inoculum source, and southwest departure. These accounted for 26 percent of the variation in infection. Most surprising was that the predicted level of infection was higher near the inoculum source, and then decreased in all directions with distance from that point. If resistance was closely tuned to the genetic variation of the fungus, the opposite pattern would be expected. Possibly variation within the rust is absent or very small and the differences among the populations, as indicated by the model, represent the interaction of the environmental conditions and genetics of the host. On the other hand, Powers and Matthews (1980) felt that the fungus has adapted to the host and consequently has produced races that are more virulent in the local sites. I find this explanation easier to accept with a system like loblolly pine; namely a fusiform rust that has been excessively disturbed, than with a system like ponderosa pine; characterized by western gall rust, which has had comparatively little disturbance.

The small but significant negative correlation of the level of infection and 3-year height is consistent with the association of growth and elevation, namely low-elevation populations grow faster and are less susceptible to western gall rust and high-elevation populations grow slower and are more susceptible. The clines in Rehfeldt's (1986) figure 2 and figure 4 in this paper show these relationships. But the association between infection and geographic pattern as predicted by the model and growth was not consistent because the fastest growing populations were from the west-central portion of the sample area (Rehfeldt 1986). These populations were the most susceptible, based on the predicted value, and from here growth and of susceptibility both decrease outwards. Rehfeldt's figure 3 on the geographic growth pattern and the geographic pattern of rust susceptibility (fig. 4) are almost identical. Thus there are two contrasting clines: (1) With geographic area, susceptibility decreasing with slower growth outwards in all directions from the inoculum source and (2) susceptibility increasing with slower growth due to an increase of elevation. I cannot explain this difference; however, the higher elevation effect, as shown by the much larger simple correlations, possibly explains why susceptibility and growth are negatively correlated. And because infection is correlated with growth when elevation is set to the mean of the populations, growth per se is not a causal factor in the differences in these patterns and is therefore possibly due mostly to environmental patterns.

Likewise it is hard to explain the association of long needles with mortality of the fungus and mortality of rust-killed trees. Rehfeldt (1986) found that the populations in the northwest portion of the sample area had the shortest needles and that the length increased in a southeasterly direction. Possibly these relationships are spurious. If real, more detailed work will have to be done to explain them.

The negative correlation of the trees that died of drought with stem reactions (either a gall or bark reaction) is also hard to explain. In other words, populations that have a higher inherent resistance to drought were more infected, that is more easily penetrated by the fungus, whether the penetration produced a gall or was repulsed by a bark reaction. This could possibly be due to chemical aspects of the stem, fatty acids, or higher moisture content of drought resistant cells—the fungus has only to penetrate the cuticle to get into a "good" environment. On the other hand, the root structure of drought-resistant provenances may produce moisture conditions in the stem that are best suited for penetration by the fungus. Answers will also have to wait for more detailed analyses of the penetration process and the environmental requirements of the process.

A major difficulty with artificial inoculation is that the trees are inoculated at one point in time. This coupled with the variation of growth initiation and rate and amount of growth among populations could lead to susceptibility patterns related to periodicity instead of inherent resistance of each population. But correlations of the growth data, either from the field or greenhouse, with total stem symptoms (galls plus bark reactions) were all very low and nonsignificant, indicating no relationship of initial infection level with growth characters for populations. I assumed therefore that all the populations had an equal chance of becoming infected during the period of inoculation and that differences would be due to the inherent genetic nature of the population in terms of susceptibility to gall rust and not to its periodicity.

MANAGEMENT IMPLICATIONS

In terms of tree improvement, there appears to be little danger in moving seed within the middle Columbia River system unless a particularly susceptible stand unknowingly is chosen for the source of seed. Thus, it is important for forest managers to closely inspect stands prior to seed collection to determine the level of susceptibility to western gall rust. Further, because some individuals are highly susceptible, care must also be taken in selecting seed trees for natural regeneration, or in selecting trees to include in tree improvement programs.

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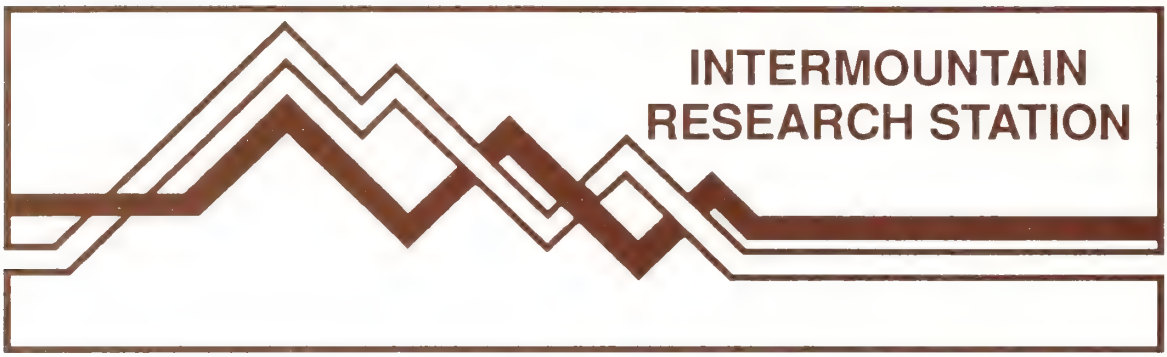
Differences in susceptibility among provenances of ponderosa pine were observed in response to artificial inoculation by western gall rust. The northern inland populations were highly resistant. Only 28 percent of the seedlings had galls 39 months after inoculation. Three major resistant reactions were observed: no symptoms, visible bark reactions, and fungus causing an initial infection but subsequently dying. Relationships were detected between infection level and elevation and geographic area. Most of the variation among provenances appeared to be random.

KEYWORDS: rust resistance, disease resistance, provenance test, artificial inoculation



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**Intermountain
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INT-417

December 1989

Comparison of Overstory Canopy Cover Estimates on Forest Survey Plots

Renee A. O'Brien

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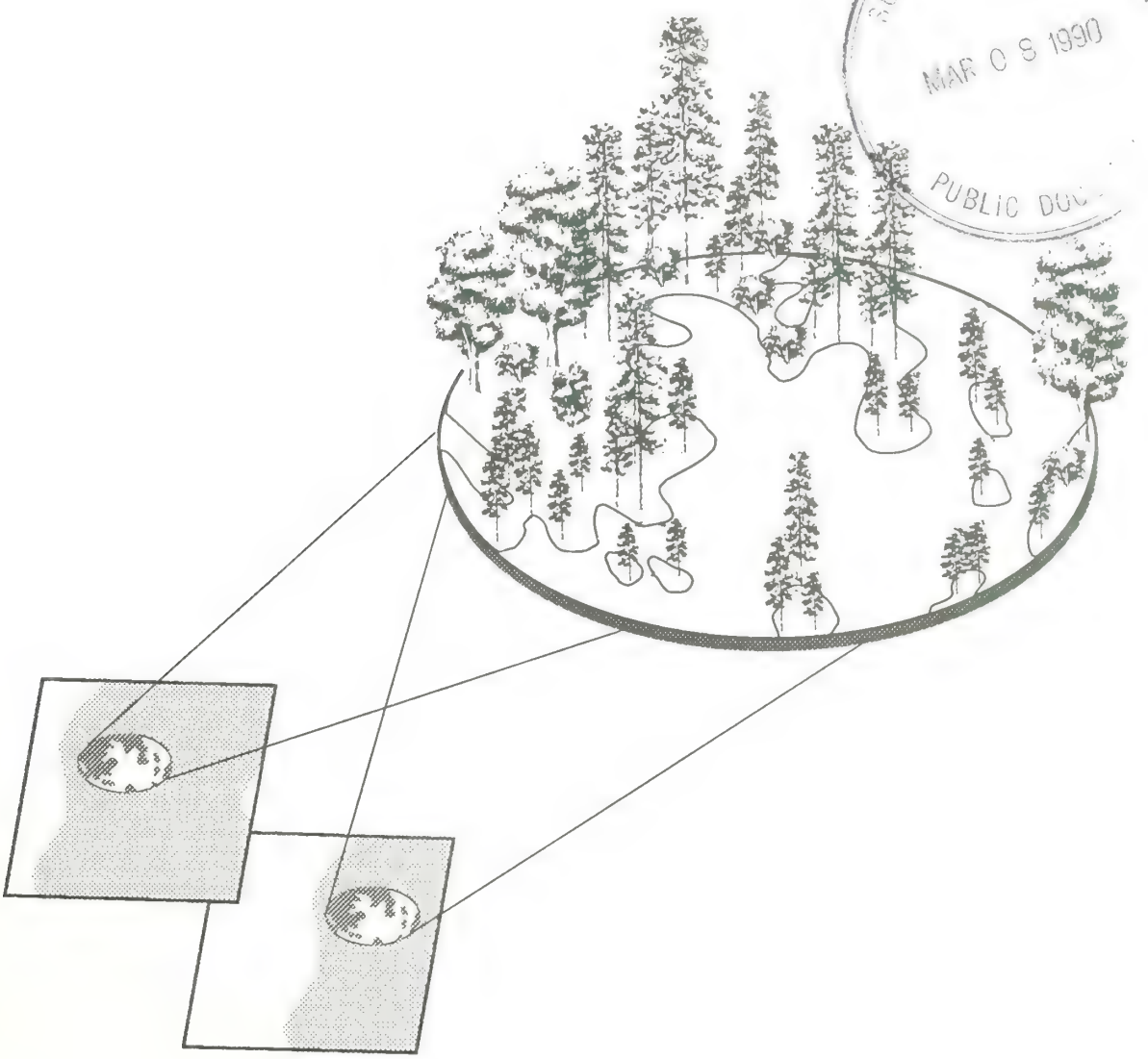

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RESEARCH SUMMARY

Two methods of overstory canopy cover assessment currently in use by Forest Survey—field photo and calculated—were compared to two alternate methods, stereo-plotted and line-intercept. The line-intercept method was used as the control. The number of transects needed to obtain a reasonable estimate of overstory canopy cover using the line-intercept method was between 6 and 8. However, the line-intercept method is time consuming, so if there are time constraints, then field photo estimates of cover are the preferred alternative for Forest Survey.

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Comparison of Overstory Canopy Cover Estimates on Forest Survey Plots

Renee A. O'Brien

INTRODUCTION

Crown canopy cover is among the most widely used measures of abundance of plant species because it is not biased by the size or distribution of individuals (Daubenmire 1968). Crown canopy cover—simply referred to as cover—is usually expressed in terms of percentage of ground covered by a vertical projection of a plant's crown. Cover is commonly broken down into two major components: overstory or tree cover, and understory cover. Overstory cover data have many purposes. For example: predicting woody plant composition, tree volume, or potential forage production; assessing wildlife habitat; and evaluating forest pest damage.

The Forest Survey Research Work Unit of the Intermountain Research Station conducts forest inventories over much of the Rocky Mountain area. Forested land of both timberland and woodland species is inventoried. Timberland includes species such as Douglas-fir (*Pseudotsuga menziesii*), ponderosa pine (*Pinus ponderosa*), and western larch (*Larix occidentalis*) that are traditionally used by the forest products industry. Woodland includes pinyon (*Pinus* spp.), juniper (*Juniperus* spp.), and other shrublike tree species.

One of the variables required from forest inventories is overstory cover. For a given site it can be used to assess distribution patterns within a region and to devise or validate relationships between overstory cover and other resource attributes on a site.

THE PROBLEM

Forest Survey uses two methods of overstory cover estimation: ocular field photo estimation and calculations based on crown dimensions. The problem is that the two methods sometimes yield widely varying values. Inventory crews ocularly estimate overstory crown cover in the field using aerial photos and on-site interpretation. These ocular estimates are recorded in direct percentages. Overstory cover is also calculated from crown measurements taken on trees sampled by field crews on Forest Survey plots.

A single, overall method needs to be chosen for consistency and efficiency. As a means of comparison with the two methods already described, two more intensive cover estimation methods were employed—the line-intercept method (Canfield 1941) and stereo-plotted cover digitized from photos. The purpose of this study is to compare the two Forest Survey methods of obtaining cover with the two alternatives, to determine the most efficient procedure for use by Forest Survey.

METHODS

The study was conducted on a subsample of Forest Survey plots in north-central New Mexico in the pinyon-juniper, ponderosa, mixed conifer, and spruce-fir forest types. The line-intercept method was chosen as the control for comparison with the other methods. It was considered the most accurate method because the intercepts were measured on the ground rather than ocularly estimated from photos, thus eliminating the subjectivity of identifying tree crowns from shadows and other illusionary effects.

Using the line-intercept method, overstory cover was measured on an acre surrounding each of 10 woodland and 10 timberland Forest Survey field plots. The proportion of the area covered by a species was determined by the length of transect intersected by that species or life form, divided by the total length of the transect. This method is most often used in understory cover estimation. It was more difficult to apply to overstory cover as height-to-tree crowns increased. Twenty 100-foot transects were systematically placed at each location (fig. 1), parallel to the slope of the plot. This number of transects was considered excessive but useful in determining the number of transects necessary for adequate evaluation.

Overstory cover was transferred from aerial photographs (1:16,000 to 1:24,000 scale) using a stereo-plotting instrument. Cover was plotted for 1 acre, at a mean scale of 1 inch equal to 200 feet (fig. 1). This stereo-plotted cover was then digitized using a two-axis digitizer with an associated error factor of one-hundredth inch. Tree cover and interspaces were digitized separately, then combined and compared to the total area of an acre. This checking procedure identified errors that were then adjusted for. The mean adjustment factor was less than 1.3 percent.

Calculated cover values were taken from the New Mexico Forest Survey field inventory data base (U. S. Department of Agriculture 1986). The values were calculated from maximum and minimum crown dimensions measured by field crews on trees sampled with a variable plot method on timberland plots and on all trees on smaller woodland plots. The sampled cover was then expanded to represent the stand being sampled. These different sampling strategies for woodland and timberland are important but were not considered part of this study and will not be discussed further in this paper. Field photo estimates of cover were made on-site by an experienced estimator for each of the 20 study plots, similar to usual Forest Survey practice.

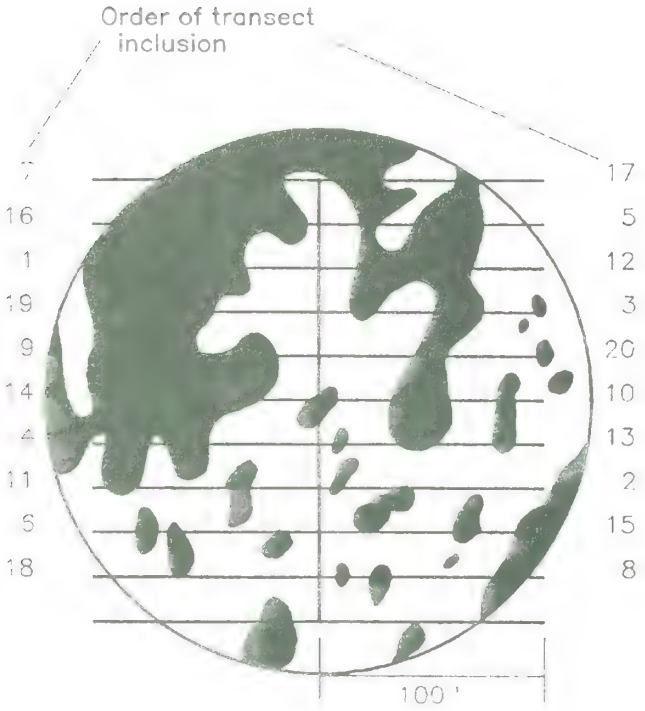

Figure 1—Map of stereo-plotted and digitized cover from 1-circular-acre timberland plot, with transect pattern overlaid. The numbers listed along the outside edges of the transect pattern illustrate the order of transect cover inclusion into the running mean.

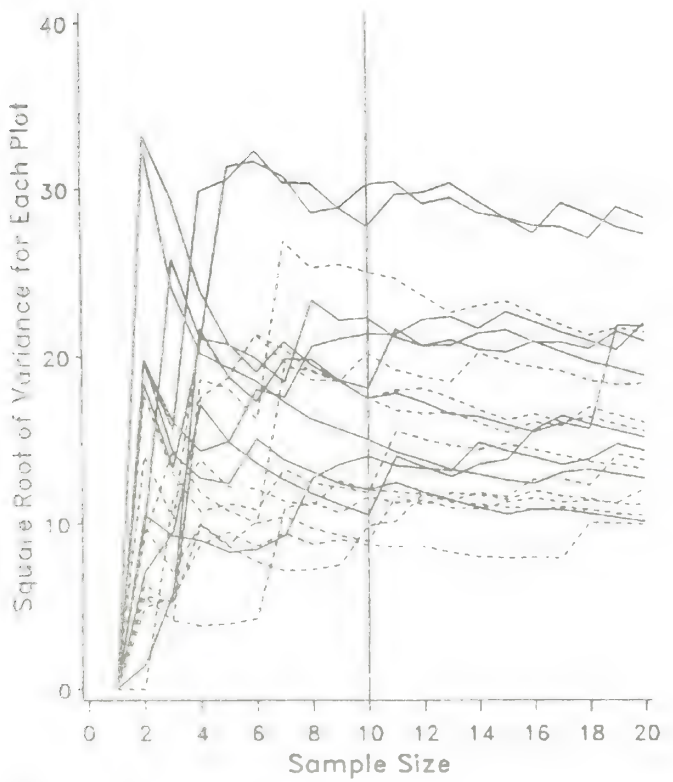

Figure 2—Square root of variance plotted against number of transects sampled—timberland (solid lines) and woodland (dashed lines). Vertical line denotes the sample size where variances more or less stabilize.

The line-intercept method, used as the control, was compared to the other methods in two ways. The first mode of comparison used 95 percent confidence intervals computed around the control and centered on a zero mean difference. A method was considered significantly different from the control if its difference from the control fell outside the confidence interval. Confidence intervals were calculated using the *t*-statistic and the variance of cover among 10 line-intercept transects. The choice of 10 transects for each plot seemed appropriate because the variance stabilized after 10 transects (fig. 2). The formula used was:

$$\text{Confidence Interval} = 0 \pm 2.93 \sqrt{\text{VAR}/10}$$

where VAR = variance of the first 10 transects (diagrammed in fig. 1) for each plot.

The second mode of comparison was overall mean difference of each method from the control. To avoid confusion when speaking of differences between values taken in percentage, hereafter no units will be mentioned. In other words, a difference between 20 and 30 percent is listed as 10.

Determination of the optimum number of transects needed to obtain reasonable cover estimates was made using running means (Kershaw and Looney 1985). The basic premise behind the running mean method is that an adequate sample size has been reached when additional samples do not significantly affect the mean. Transects were included in the running means in a random order, which is listed in figure 1.

RESULTS AND DISCUSSION

Cover estimates obtained with the four methods for each of the 10 timberland and 10 woodland locations are presented in table 1. Included are the results of the confidence intervals placed around the line-intercept control to evaluate the differences between each method and the control. On the average, using any method, cover estimates fell outside the 95 percent confidence interval placed around the line-intercept values about half the time. Stereo-plotted estimates of cover fell outside the 95 percent confidence interval less often than field photo estimates of cover, which in turn fell outside less often than calculated cover estimates. In general, woodland cover estimation was better than timberland cover estimation using any method. This could be because of the taller, multistoried nature of timberland versus the shorter, single-storied woodland.

Table 2 includes the overall mean difference between line-intercept and the other three methods, and the standard deviation of the differences. The field photo estimate had the lowest mean difference from line-intercept on all plots, but all estimates had similar standard errors. Negative mean differences for field photo estimates may indicate an overestimation bias (table 2).

Table 1—Percentage line-intercept cover (control) and other percentage cover estimates—calculated from crown measurements, ocularly estimated from photos in the field, and stereo-plotted and digitized from photos—for each study plot

Forest type	Line-intercept (control)	Stereo-plotted	Field photo estimate	Calculated
		Percent		
Timberland	24	12 **	25	11 **
Timberland	25	11	14	2 **
Timberland	31	41 **	44 **	20 **
Timberland	39	40	55 **	20 **
Timberland	40	21 **	28 **	29
Timberland	51	57	58	67
Timberland	51	42	51	30 **
Timberland	56	25 **	39 **	45
Timberland	62	39 **	52 **	43 **
Timberland	67	88 **	87 **	35 **
Woodland	6	4	2 **	7
Woodland	9	5	12	8
Woodland	16	9	15	5 **
Woodland	25	14 **	21	15 **
Woodland	27	24	34	12 **
Woodland	37	28	35	21 **
Woodland	43	42	62 **	30 **
Woodland	43	31	20 **	39
Woodland	43	37	42	53
Woodland	55	72 **	78 **	29 **

** Cover estimates whose differences from the control fell outside a 95 percent confidence interval placed around the control.

Table 2—Mean difference and variance of the differences between line-intercept percentage cover values and other percent cover estimates

	Cover estimation method	Mean difference	$\sqrt{\text{Variance}}$
		Percent	
Timberland only	Calculated	14	13
	Photo estimated	–1	13
	Stereo-plotted	7	16
Woodland only	Calculated	9	10
	Photo estimated	–2	13
	Stereo-plotted	4	8
Timberland and woodland combined	Calculated	12	11
	Photo estimated	–1	13
	Stereo-plotted	6	13

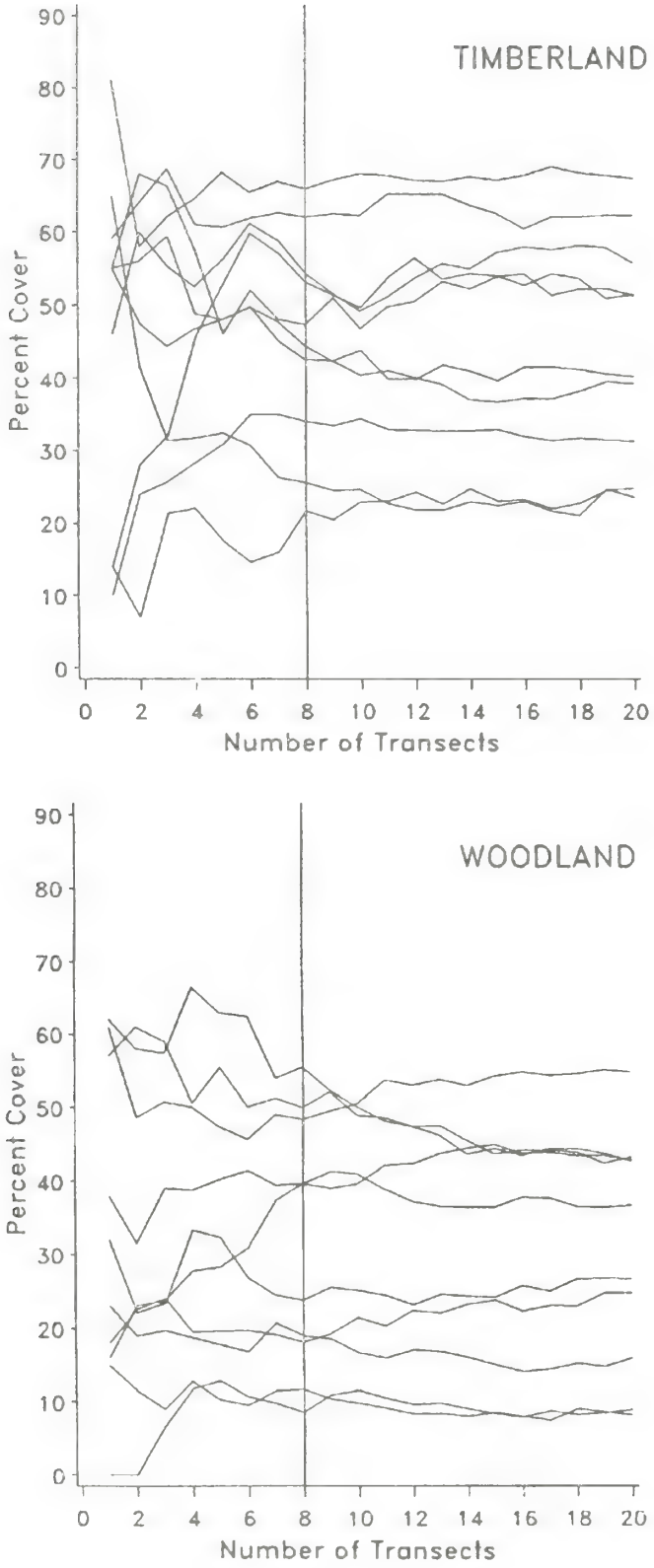

Figure 3—Relation of mean line-intercept cover to number of transects sampled, by timberland and woodland. The Y-axis is mean cover for all 20 transects (control) for each of 10 timberland and 10 woodland plots. Vertical lines denote the optimum number of transects.

Graphical analysis was used to determine the optimum number of transects for cover estimation on an acre (fig. 3). Apparent stabilization of the running mean lines in general occurred at about seven or eight transects; fewer for woodland plots at low cover and for timberland plots at high cover.

Arbitrary standards have been set by requiring that a sample be within 5 or 10 percent of some maximum sample (Mueller-Dombois and Ellenberg 1974). In this study, the average number of transects needed to be within 10 percent of the mean of all 20 transects, on all 20 plots, was six. Therefore, between six and eight transects should give an adequate sample of overstory cover in most cases.

CONCLUSIONS

On the average, using any method, cover estimates fell outside the 95 percent confidence interval placed around the line-intercept values about half the time (table 1). The field photo estimates fell outside the confidence interval fewer times than the other Forest Survey method, calculated cover. Field photo estimates also had the lowest overall mean difference in percentage (–1) from the line-intercept control, as compared with a mean difference of 6 for stereo-plotted cover and 12 for calculated cover.

The stereo-plotted cover method, which was used in this study as an alternative means of comparison, is too time consuming and takes too much specialized equipment to be used by Forest Survey on each plot. The results of this method fell outside the confidence interval fewer times than the field photo estimates but had a greater mean difference from the line-intercept control.

The calculated cover method proved to be the most different from the control in terms of the confidence interval and overall mean difference. Some of this difference can be attributed to different plot sizes and tree sampling techniques not discussed in this paper.

The line-intercept method, which we have assumed is the most accurate cover evaluation method, could be used on Forest Survey plots but is still much more time consuming than photo estimation. After a sample size of eight, the number of transects made little difference when compared to the mean of 20 transects. In general, woodland cover estimation was better than timberland cover estimation using any method.

If time constraints do not permit line-intercept transect layout, field photo estimates of cover are the best alternative for Forest Survey. Other researchers have advocated photo estimation. Vora (1988) found no significant difference between ocular and spherical densiometer cover estimates and recommended ocular estimates in some cases. Vales and Bunnell (1988) showed that different observers' ocular estimations of forest overstory cover were similar. Photo estimates done on-site are probably better than photo estimates done in the office because changes since the photos were taken and areas in question such as shadows and understory vegetation can be corrected for ocularly. Adequate training is needed, of course, to ensure that consistent, accurate estimates are obtained.

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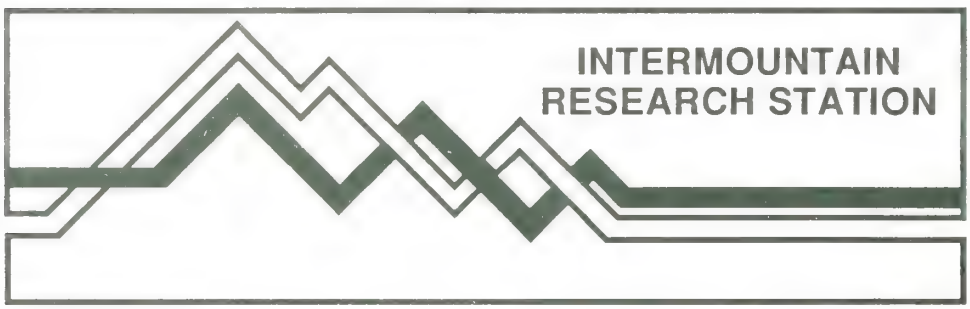
O'Brien, Renee A. 1989. A comparison of overstory canopy cover estimates on Forest Survey plots. Res. Pap. INT-417. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 5 p.

Two methods of overstory canopy cover assessment currently in use by Forest Survey—field photo and calculated—were compared to two alternate methods, stereo-plotted and line-intercept. The line-intercept method was used as the control. The number of transects needed to obtain a reasonable estimate of overstory canopy cover using the line-intercept method was between 6 and 8. However, the line-intercept method is time consuming, so if there are time constraints, then field photo estimates of cover are the preferred alternative for Forest Survey.

KEYWORDS: overstory cover, line-intercept, field photo estimates, stereo-plotted cover



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Predicting Salability of Timber Sale Offerings in the Forest Service Northern Region

Michael J. Niccolucci

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RESEARCH SUMMARY

Timber sale planning is a complex, expensive process. Developing a sale to the point where it is ready for auction requires the efforts of many natural resource specialists, many hours, and many dollars. The common expectation is for the sale to sell at initial auction. But many timber sales receive no bids, meaning they do not sell at their initial offering. Given the large investment involved, the occurrence of unsold sales is not desirable. Unsold sales also raise the question of organizational competence.

Knowing the likely outcome of a timber sale offering, particularly in early design stage, is important to the manager. This information can be used to modify the timber sale thereby increasing its likelihood of selling. The research reported here developed and compared two approaches to statistical classification, intended to predict salability at various points in the sale planning process. Classification results were statistically compared based on geographical zone models, models at various points in the timber sale planning process, and the classification methods used.

Data used in this study came from a sample of 389 sold and unsold timber sales in the Northern Region of the Forest Service, U.S. Department of Agriculture. The region was further divided into two geographical zones—east and west of the Continental Divide. Discriminant analysis and logistic regression were used to develop statistical equations to classify timber sales into groups of sold and unsold. Equations were designed to be used at three points in the "Gates" timber sale planning process, all before the actual bidding. The quantity and quality of information increases as the sale proceeds from one gate to another.

The accuracy of the equations increased as the timber sale progressed through the Gates process. Equations at the first gate, approximately 7 to 10 years before the auction date, correctly classified about 65 percent of the sales, based on only general sale characteristics. The equations for the next gate, 1 to 3 years before the auction, correctly classified 74 percent of the sales. Equations at the final gate before the auction correctly classified about 84 percent of the sales.

Statistical analyses were conducted to test for differences in classification success between geographical zones within the Northern Region, between statistical modeling techniques, and between phases in the timber sale planning process. Statistically significant results were found between geographical zones and sale phases, but no statistical difference in classification success could be found between statistical modeling techniques.

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Predicting Salability of Timber Sale Offerings in the Forest Service Northern Region

Michael J. Niccolucci

INTRODUCTION

Timber sales play an important role in achieving forest management goals and objectives—providing wood raw materials, nontimber outputs, and government revenue. The sale is planned by foresters, engineers, and other specialists. It takes approximately 2 to 10 years to develop a timber sale, depending upon sale size and complexity. Once the timber sale plan is finalized, it is offered to the public for purchase, fully expecting the sale to sell at its initial offering.

But sometimes a timber sale offering receives no bids. The sale remains unsold. During 1980 through 1985, approximately 20 percent of volume offered for sale received no bid. An offering that fails to sell, given all of the hours of planning needed, can be viewed as a waste of dollars and human resources. Even if revised, reoffered, and later sold, these unsold offerings may be obviously seen as evidence of poor planning, professional incompetence, or timber supply exceeding demand. Revisions require added expense and still do not guarantee a more appealing offering.

Forest Service managers need reliable, defensible tools to better predict salability. Also, given the years needed to plan a sale, the sooner salability is known, the better. Timber sale specialists can then either modify the sale design or simply offer the timber sale without further modification in light of expected salability.

Currently, Forest Service managers in the Northern Region have been using Transaction Evidence Equations (Merzenich 1985), Timber Sale Feasibility Analysis (Peterson 1980), and DLOGPRICE Economic Model (Artley 1986) to quantify salability. Transaction evidence is a multiple regression approach used to predict stumpage value. Because these equations are typically based on sold sales only, they cannot be used to make reliable statistical predictions regarding unsold sales. The sale feasibility and DLOGPRICE models both rely on the calculation of a value-cost ratio. Because the statistical significance of these ratios cannot be tested, these procedures cannot be rigorously defended.

The research being reported here was designed to develop and compare two statistical approaches to predicting timber salability at various points in the sale planning process. Several questions were addressed:

1. Is one approach consistently better than the other?
2. Does our ability to predict salability improve as the sale gets closer to the auction date?
3. Does geographical zone variation affect salability prediction?

METHODS

Methods used in this study fundamentally reflect research choices about statistical classification methods and how the timber sale planning process is envisaged. The planning process provided this study a timeframe within which to analyze timber sales. Fortunately, the Forest Service currently uses a planning process that contains the desired timeframe. Because a timber sale selling or not selling is a dichotomous event, the desired statistical technique should be capable of classifying events into those classes. Logistic regression and discriminant analysis were the classification methods selected.

Timber Sale Preparation—The Gates Process

The Forest Service currently uses a planning and decision making process called "Gates" to design timber sales (USDA FS 1985, 2431.2). This process encompasses a series of activities that begins with the identification of a sale area and ends with a sale award. Sale planning activities must pass through six reporting points, called "gates."

Gate 1: Sale preparation begins. This entails identifying the purpose and the need for the sale; identifying public issues; identifying the resource opportunities in the sale area, and so on. Preliminary sale volume and sale area estimates are also produced.

Gate 2: Alternative sale area designs are developed. Environmental effects are analyzed and a preliminary economic analysis is completed. Gate 2 results in selection of a preferred alternative.

Gate 3: The activities leading to sale plan implementation are performed. Preparation of the contract, data gathering, and the necessary outline to support the appraisal are examples of these activities. The sale passes through gate 3 when the fieldwork and the timber sale report are completed.

Gate 4: Necessary engineering, logging, and environmental cost information is gathered. Timber value is set, the appraisal is prepared, and the total sale package is reviewed.

Gate 5: Bids are accepted and the successful bidder is determined. The output is the bid report.

Gate 6: The winning bidder is evaluated with respect to financial qualifications, Equal Employment Opportunity clearance, and so on. The timber sale passes through gate 6 when all requirements are met; the award of the contract is the output.

The "gates" are important to this study because they not only progress temporally toward the actual implementation of the timber sale, but they also depict increasing quantity and quality of information that can be utilized by statistical classification models. Because gates 5 and 6 occur after the sale is sold (or not sold) they are of no use in predicting salability and will not be considered further.

At gate 1 an area is brought into the planning process through development of a position statement—a document that is a prerequisite to listing a proposed timber sale on the timber sale action plan (USDA FS 1985, 2414.27). At this point, 10 years from the auction date, very little site-specific information is known. Examples of information known at this gate are slope, elevation, and acreage within the proposed sale area. Over the long time span of sale development many external influences may alter salability.

Gates 2 and 3 are closely related and will be treated as a single, composite gate. They deal with developing a sale area design and preparing for sale plan implementation. At these gates specific sale characteristics are developed. Sale characteristics include number and size of the cutting units, the volume-per-acre harvested, the miles of road construction, the silvicultural systems needed, the logging method required, and so forth. Gates 2 and 3 occur about 1 to 3 years before the auction date.

Gate 4, the final gate for predicting salability, completes the package by generating the appraisal. At this gate, the planner's sale design decisions are converted into appraisal information—dollars per thousand board feet. Information generated at this gate includes stump-to-mill costs and the advertised selling rate. Gate 4 occurs about 3 months before the auction.

Classification Methods

The major factor affecting selection of statistical classification methods is the dichotomous nature of the dependent variable. In this problem, the dependent variable takes on two values (0 = unsold, 1 = sold) and identifies group membership. For this class of problem, potentially useful methods are limited to regression analysis, discriminant analysis, and logistic regression. The method of regression analysis was discarded because of the potential violations of certain key assumptions, principally the variance of the error term is not constant for all observations, and the predicted values are not guaranteed to lie in the (0, 1) interval (see Pindyck and Rubinfeld 1981). The methods of logistic regression and discriminant analysis seem well suited to the problem of predicting salability.

LOGISTIC REGRESSION

Logistic regression relates a qualitative dependent variable, such as "sold" or "unsold" timber sales, to independent predictor variables through a cumulative logistic probability function (see Maddala 1983; Pindyck and Rubinfeld 1981). Parameter estimation is based on maximum likelihood estimation. These estimates have several desirable properties, such as all parameters being consistent and efficient asymptotically (Pindyck and Rubinfeld 1981). All parameter estimators are known to be normal, therefore the t-test can be applied to test for significance. Also, research has shown that if certain discriminant function assumptions are violated, the logistic regression provides better prediction results (Press and Wilson 1978).

The logistic regression predicts a probability of an event occurring. The general model is specified as:

$$\text{Probability}_i = \frac{e^Y}{1 + e^Y} \qquad (1)$$

Probability_i is the probability of an event occurring (sale selling), e is the base of natural logarithms (approximately 2.718), and Y is estimated:

$$Y = B_0 + B_1X_1 + B_2X_2 + \ldots + B_iX_i + E_i. \qquad (2)$$

Equation 2 above is presented in this research. To predict a probability that an event will occur, you must first calculate a Y and then substitute that value into equation (1).

Given the predicted probability that an offering will sell, a decision rule needs to be adopted to perform classification. The common decision rule is based on a probability of one-half. If the probability is greater than or equal to 0.50, the sale is predicted to be a sold sale. If the probability is less than 0.50, the sale is predicted to be an unsold sale. This specific decision rule will generate a specific classification result.

Most of the following results are based on the 50 percent decision rule discussed above. The effect of changing this rule is also explored.

DISCRIMINANT ANALYSIS

Discriminant analysis is the traditional classification technique. The basic strategy in discriminant analysis is to form an equation (discriminant function) that uses independent variables to classify observations into designated groups (sold and unsold timber sales). The discriminant function (equation) has the following form:

$$L = B_1X_1 + B_2X_2 + \ldots + B_iX_i \qquad (3)$$

where L is the dependent variable (sold and unsold sales) and X_1 through X_i are independent variables. The common expectation is the production of a discriminant function (equation) that optimally separates the designated groups.

The linear discriminant function and its classification rule depend on several statistical assumptions (Maddala 1983). If the assumptions are violated, corrective procedures are recommended (Johnson and Wichern 1982; Meddala 1983; Press and Wilson 1978). The linear discriminant functions were tested for compliance with the statistical assumptions and corrective procedures applied when necessary.

Classification can be achieved using either Fisher's linear discriminant function (equation presented above) or classification functions (see Morrison 1976 for a discussion on classification functions—classification functions presented in tables 10 through 15, appendix B). Classification depends on the calculated discriminant score and a critical value. If the calculated discriminant score is greater than zero (the critical value) it is assigned to the sold sales category, and if less than zero to the unsold sales category.

Study Design

The Gates timber sale planning process provided the framework for this analysis. As the sale progresses from gate 1 to gate 4, site, sale, appraisal, and economic information is generated. This information was used to develop the equations. The gate 1 equation is based on the general site characteristics known at that time in the planning process. The gate 2-3 equation is based on information from gate 1 (site characteristics) plus information from gates 2 and 3 (sale characteristics). The third equation, based at gate 4, uses all prior information plus the appraisal information generated at this gate. If one chooses to use measures of economic expectations as independent variables, gate 4 would be the appropriate gate. Estimates of economic expectations were not used.

I analyzed timber sales auctioned during January 1980 through December 1985 on National Forests in the Northern Region of the Forest Service. All timber sales were competitively auctioned and were of at least $2,000 minimum value. The sampling period consisted of the high markets of the early 1980's, a major recession in 1982 and 1983, and a recovery during 1984 and 1985. Given that the major thrust of this research was the development and comparison of methods that quantify salability, the sample diversity was not a hindrance. But the equations should be used only to predict salability for sales that will be competitively auctioned.

I randomly sampled 389 sold and unsold timber sales from the 13 National Forests in the Northern Region. Of the 389 sales, 349 timber sales were sampled on the "westside" National Forests (Bitterroot, Lolo, Flathead, Kootenai, Idaho Panhandle, Clearwater, and Nez Perce). Of the 349 westside timber sales, 204 were sold timber sales; the remaining 145 timber sales were unsold. I sampled 40 timber sales on the "eastside" National Forests (Custer, Gallatin, Beaverhead, Helena, Lewis & Clark, and Deerlodge). They were composed of 26 sold and 14 unsold sales.

Analytical Procedures

MODEL CONSTRUCTION

The equations were checked for violations of the assumptions and were corrected if appropriate. Given the empirical nature of equation development, Wilk's lambda (stepwise procedure) was used to generate the final discriminant functions. For logistic regression, an "all-possibles" regression subroutine based on ordinary least squares was used to develop preliminary equations. Of course, the timber sale and economic characteristics used were considered logical variables in determining sold and unsold timber sales.

Both statistical classification methods were developed using SPSSX (Nie 1983) and BMDP (Dixon 1981) statistical software on a Vax 8600 computer.

EVALUATION CRITERIA

Using either the classification functions or Fisher's linear discriminant function, I produced a classification matrix that presents the predicted classification results. The classification matrix is a tabular method used to present the percentage correctly and incorrectly classified. Another method used to measure goodness of fit is the Holdout method (Lachenbruch 1975), also known as the Jackknife method. This method predicts the group to which a sale belongs when the sale is not involved in the model-building process. This technique generates a better estimate of the error variance than the classification method described above. Both of these methods are used to produce classification results for the discriminant functions.

The logistic regression equation predicts the probability of a sale being sold given sale attributes and market information. Since it predicts a probability, we must adopt a rule that aggregates these probabilities into groups. The decision rule adopted aggregated sales with predicted probabilities greater than or equal to 0.50 into the sold sales group. If the predicted probability is less than 0.50, the sale is predicted to be an unsold timber sale. Once the decision rule was implemented, a classification matrix was constructed, indicating how well the equation predicted sold and unsold timber sales.

CUTOFF POINTS

Particularly important is the link between probability levels, classification results, and the cost of making a decision error. The decision rule of 0.50 probability implies the costs of misclassifying sold and unsold sales is equal. But it may be more costly from a managerial standpoint to classify a sale as salable, when actually it will not sell.

Analysts and decision makers are free to adopt any decision rule. A different decision rule will lead to different classification results. Decision rules imply an underlying cost of making a decision error. These costs are not consistent from user to user. A particular land manager may view misclassification of a predicted sold sale more costly than misclassification of a predicted unsold sale. The land manager's cost of misclassification will lead to a particular decision rule, and thus, different classification results.

Seven cutoff points (probability levels) were chosen to investigate the changes in classification results: 0.20, 0.25, 0.33, 0.50, 0.67, 0.75, and 0.80. The posterior probabilities were used as the discriminant model's predicted probabilities of a sale selling. The posterior probabilities provide a continuous prediction of salability and allow the cutoff points (decision rule) to vary at the levels defined previously.

As stated previously, the logistic regression predicts a probability, and therefore adapts easily to this analysis.

CATEGORICAL ANALYSIS OF VARIANCE

Categorical analysis of variance (Bishop and others 1975) was used to analyze the dependent variable, percentage correct (*%c*), based on independent variables, classification method (*cm*), gates (*g*), and geographical zones (*z*). The results of this analysis statistically quantified the benefits derived by having employed different classification methods, gates, and geographical zones.

The mathematical equation is:

$$\%c_{ijk} = M + cm_i + g_j + z_k + I_{ijk} + e_{ijk}$$

where I_{ijk}, e_{ijk}, and M are the interaction term, error term, and the overall mean, respectively.

RESULTS AND DISCUSSION

In total, 12 classification equations were developed to predict salability—two statistical classification methods for each of three gates in the sale planning process on each of two geographical zones within the Northern Region. Table 1 provides an overall summary of the results, showing that the percent correctly classified ranged from 59 to 90.

Table 1 suggests that classification success steadily improved with progression from gate 1 to gate 4, that eastside sales are more successfully classified, and that the two analytical procedures produce similar results. In fact, these impressions are correct, as will be shown in later statistical analysis.

The 22 significant variables used in the equations are defined in table 2. As indicated earlier, measurements on sale variables were made from timber sale records and economic variables from government publications.

Table 1—Overall summary of classification success

Gate	Subregion	Logistic regression	Discriminant analysis
		Percent correctly classified	
1	Eastside	65.0	72.5
	Westside	63.3	59.0
2-3	Eastside	80.0	77.2
	Westside	70.2	68.8
4	Eastside	85.0	90.0
	Westside	77.4	77.9

Table 2—Independent variables used in study

Variable	Description	Units
TOTVOL	Total sale volume harvested	M bd. ft. (Scribner)
TOTSALE	Total sale area	Acres
AVGSLOPE	Average slope	Percent
ALPM	Average logs per thousand	Number
TOTROAD	Total road construction	Miles
NEW	New road construction	Miles
RECON	Old road reconstruction	Miles
ACRES	Acres harvested in sale	Acres
DENSE	Acres harvested divided by total sale area	Number
VPA	Volume per acre harvested	M bd. ft. (Scribner)
DEAD	Percent volume dead white pine or lodgepole pine	Percent
%TRAC	Percent volume tractor yarded	Percent
%CABLE	Percent volume cable yarded	Percent
TRACDIST	Average maximum tractor yarding distance	Feet
STUMPMILL	Felling and bucking + skidding and loading + haul + slash + road + advertised rate	$/M bd. ft.
ADVRATE	Minimum bid price	$/M bd. ft.
SPLT	Selling price, lumber tally	$/M bd. ft.
PMETH	Contract price escalation clause	1 = Yes 0 = No
HAULRAT	Haul distance to primary appraisal point divided by haul distance to secondary appraisal point	Number
$UNCUT_{t-3}$	Uncut volume under contract lagged 3 months	Number
$EXCH_{t-3}$	U.S./Canadian exchange rate lagged 3 months	Number
COMPMILL	Competing mills at appraisal point	1 = Yes 0 = No
LMBRPROD	12-month percentage change in Inland region lumber production	Number

Gate 1

Gate 1 provides very little information that can be used to develop the equation. Only general site information (slope and elevation) and early volume estimates are known at this time. It is therefore difficult to predict group membership at this point.

EASTSIDE EQUATIONS

The gate 1 eastside equations and classification results are found in table 3. In general, the eastside equations indicate that sale size (TOTVOL and TOTSALE) has a positive influence on salability meaning that sales with larger volumes and of larger size increase the likelihood of selling. The standardized discriminant coefficients indicate that total volume (TOTVOL) is the most important determinant of salability.

In terms of significant variables, the logistic regression and the discriminant function are very similar. Their prediction results are noticeably different, however (table 3b). The logistic regression correctly classifies 42.9 percent of the unsold sales, while the discriminant function correctly classifies 85.7 percent. The logistic regression has the advantage of predicting sold sales, but the difference is not substantial. Given its unsold sales prediction accuracy, the discriminant function correctly classifies a higher percentage of all the sales, 72.5 percent compared to 65.0 percent. Also, the holdout method indicates that the discriminant error rates (percent correctly classified) are quite stable, with the largest percentage change occurring within the unsold sales class.

WESTSIDE EQUATIONS

Table 4 presents the westside equations and classification results. Both equations contain the same statistically significant variables, total volume (TOTVOL), total sale acres (TOTSALE), and average slope (AVGSLOPE). The westside equations indicate that sale size and slope are significant determinants of sold and unsold sales. On the westside forests, however, the total sale acres have a negative effect on salability. The average slope indicates offerings found on steep slopes are more likely to be unsold. The standardized discriminant coefficients indicate that total sale acres is the most important determinant of salability.

Table 4b presents the westside gate 1 classification results. A higher percentage of unsold sales are correctly classified by the discriminant function. But the logistic regression correctly classifies a higher percentage of sold sales. Overall the logisitic regression correctly classifies 63.3 percent of the sales, in comparison to 60.2 percent, for the discriminant function. The holdout classification results indicate the discriminant results are quite stable; the percentage correctly classified is identical for both classification measurements.

Table 3—Gate 1 eastside equations and classification results

A. Equations

	Logistic regression		Discriminant analysis	
Variable	Coefficient	(Std Err)	Coefficient	(Std Coeff)
TOTVOL	0.00048	(0.00022)		
$(TOTVOL)^{1/2}$			0.027	(0.575)
TOTSALE			.0003	(.487)
Constant	–.276	(.498)	–1.582	

B. Classification results

		Logistic regression		Discriminant analysis	
Actual group	Total sales	Correct predict	Percent correct	Correct predict	Percent correct
Unsold	14	6	42.9	12	85.7 (78.6)[1]
Sold	26	20	76.9	17	65.4 (61.5)[1]
All sales	40	26	65.0	29	72.5 (67.5)[1]

[1]Indicates percent correctly classified using the holdout method.

Table 4—Gate 1 westside equations and classification results

A. Equations

	Logistic regression		Discriminant analysis	
Variable	Coefficient	(Std Err)	Coefficient	(Std Coeff)
TOTVOL	0.00008	(0.00004)		
Ln(TOTVOL)			0.496	(0.742)
$(TOTSALE)^{1/2}$	–.032	(.008)		
Ln(TOTSALE)			–.734	(1.135)
AVGSLOPE	–.032	(.010)	–.053	(.659)
Constant	1.984	(.380)	2.562	

B. Classification results

		Logistic regression		Discriminant analysis	
Actual group	Total sales	Correct predict	Percent correct	Correct predict	Percent correct
Unsold	145	54	37.2	92	63.4 (63.4)[1]
Sold	204	167	81.9	114	55.9 (55.9)[1]
All sales	349	221	63.3	206	59.0 (59.0)[1]

[1]Indicates percent correctly classified using the holdout method.

Gates 2 and 3

At gates 2 and 3, the road network, size and number of cutting units, yarding system, silvicultural methods, and harvested acres are defined. These are examples of variables used to develop the gate 2-3 equations. At this point, the auction date is approximately 1 to 3 years in the future.

EASTSIDE EQUATIONS

The equations and classification results are presented in table 5. The gate 2-3 eastside equations have the same significant variables and differ only in the transformations used. The equations indicate the more volume harvested (TOTVOL), the more likely the timber sale will be sold. The standardized discriminant coefficient for total volume harvested indicates it is the most important determinant of sold and unsold sales. If the average logs per thousand board feet (ALPM) is high, it is more likely that the sale will be unsold. The ALPM variable is the number of logs to be moved; the more pieces moved the less likely the sale will be sold. The final variable—miles of total road construction (TOTROAD)—represents the initial development necessary to harvest the sale. The miles of road construction affect the sale by restricting the number of potential purchasers and introduce an additional source of risk by delaying the harvest (Johnson 1979).

The classification results for the two methods are almost identical (see table 5b). The difference lies in the number of sold sales correctly predicted. The logistic regression correctly classifies an additional sale. The discriminant function classification results are very stable. The classification results are identical for both measures of prediction accuracy.

The TOTVOL variable is the only gate 1 variable remaining. TOTSALE has been displaced by gate 2-3 variables (ALPM and TOTROAD). ALPM and TOTROAD are more specific timber sale information and allow prediction accuracy to increase.

Using gates 2 and 3 information, the equations have improved the overall classification results by 23.1 percent for the logistic regression and 6.9 percent for the discriminant equation.

WESTSIDE EQUATIONS

The westside gate 2-3 equations are quite similar in terms of significant variables. Total road construction (TOTROAD) was a more desirable variable in the logistic regression than was miles of new road construction (NEW) and miles of road reconstruction (RECON).

The equations and classification results are presented in table 6. The following variables have a positive effect on a sale selling: the ratio of acres harvested to total sale acres (DENSE), volume-per-acre harvested (VPA), percentage of volume tractor yarded (%TRAC), and the average maximum tractor yarding distance (TRACDIST). The remaining significant variables, miles of road construction (TOTROAD, NEW and RECON), percentage of volume of dead lodgepole or dead whitepine (DEAD), and the average logs per thousand board feet (ALPM) have a negative

Table 5—Gate 2-3 eastside equations and classification results

A. Equations

	Logistic regression		Discriminant analysis	
Variable	Coefficient	(Std Err)	Coefficient	(Std Coeff)
Ln(TOTVOL)	3.812	(1.448)		
$(TOTVOL)^{1/2}$			0.073	(1.537)
Ln(ALPM)			–.962	(.487)
ALPM	–.042	(.060)		
$(TOTROAD)^{1/2}$	–3.440	(1.342)	–1.105	(–1.294)
Constant	–18.426	(7.699)	2.142	

B. Classification results

		Logistic regression		Discriminant analysis	
Actual group	Total sales	Correct predict	Percent correct	Correct predict	Percent correct
Unsold	14	10	71.4	10	71.4 (71.4)[1]
Sold	26	22	84.6	21	80.8 (80.8)[1]
All sales	40	32	80.0	31	77.5 (77.5)[1]

[1]Indicates percent correctly classified using the holdout method.

Table 6—Gate 2-3 westside equations and classification results

A. Equations

	Logistic regression		Discriminant analysis	
Variable	Coefficient	(Std Err)	Coefficient	(Std Coeff)
DENSE	0.864	(0.420)		
$(DENSE)^{1/2}$			1.344	(0.324)
VPA	.062	(.016)		
$(VPA)^{1/2}$			.489	(.651)
Ln(TOTROAD)	–.200	(.112)		
$(NEW)^{1/2}$			–.230	(–.301)
$(RECON)^{1/2}$			–.064	(–.082)
DEAD	–.026	(.010)		
Ln(DEAD)			–3.944	(–.373)
$(ALPM)^2$	–.0004	(.00030)		
$(ALPM)^{1/2}$			–.261	(–.269)
%TRAC	.022	(.004)	.022	(.778)
$(TRACDIST)^2$	.00002	(.0000)		
Constant	–1.300	(.450)	–2.327	

B. Classification results

		Logistic regression		Discriminant analysis	
Actual group	Total sales	Correct predict	Percent correct	Correct predict	Percent correct
Unsold	145	84	57.9	101	69.7 (66.9)[1]
Sold	204	161	78.9	139	68.1 (66.2)[1]
All sales	349	245	70.2	240	68.8 (66.5)[1]

[1]Indicates percent correctly classified using the holdout method.

effect on a timber sale selling. Of the variables in the discriminant function, %TRAC is the most important discriminator (standardized coefficient = 0.778).

Comparing westside and eastside results, one can conclude that the westside timber offerings are more difficult to explain. Given the complexity, a more complicated equation is needed to produce the observed classification results. Therefore, one should not expect an identical equation structure between geographical zones.

The overall classification results for the two approaches are also quite similar (see table 6b). The logistic regression correctly classifies 70.2 percent of the sales, while the discriminant function correctly classifies 68.8 percent. The differences exist in the equation's ability to classify the individual categories. The discriminant function correctly classifies a higher percentage of the unsold sales (69.7 vs. 57.9 percent), the logistic regression correctly classifies more of the sold sales (78.9 vs. 68.1 percent). The holdout method indicates that prediction accuracy for the discriminant model is 66.5 percent, a slight decrease. Also, there is a slight decrease in the individual group classification results.

The gate 2-3 equations have changed in comparison to gate 1 to reflect the better information available. After adding the information from gates 2 and 3, the overall classification results increased from 221 to 245 (10.9 percent) for the logistic regression and from 206 to 240 (16.5 percent) for the discriminant equation.

Table 7—Gate 4 eastside equations and classification results

A. Equations

Variable	Logistic regression Coefficient	(Std Err)	Discriminant analysis Coefficient	(Std Coeff)
STUMPMILL	–0.078	(0.030)		
Ln(STUMPMILL)			–6.102	(–1.132)
TOTVOL	.0012	(.0004)		
$(TOTVOL)^{1/2}$			.037	(.783)
SPLT	.088	(.038)		
Ln(SPLT)			6.656	(.832)
Ln(ALPM)			–.615	(–.169)
Ln(DEAD)			.287	(.351)
PMETH			–.667	(–.274)
Constant	–2.620	(5.488)	–2.622	

B. Classification results

Actual group	Total sales	Logistic regression Correct predict	Percent correct	Discriminant analysis Correct predict	Percent correct
Unsold	14	10	71.4	13	92.9 (71.4)[1]
Sold	26	24	92.3	23	88.5 (73.1)[1]
All sales	40	34	85.0	36	90.0 (72.5)[1]

[1]Indicates percent correctly classified using the holdout method.

Gate 4

At the final gate before the offering, appraisal and economic information is added to site and sale characteristics. This point in the gates process can be viewed as one that converts sale characteristics information into dollars per thousand board feet. This gate is approximately 2 to 3 months before the initial offering.

EASTSIDE EQUATIONS

In general, the gate 4 eastside equations indicate that the stump-to-mill cost (STUMPMILL), the size (TOTVOL), and the price of final product derived from the logs (SPLT) are the important factors affecting salability (table 7). The discriminant function contains three additional variables, the natural logarithm of average logs per thousand, ln(ALPM), the natural logarithm of percent volume dead white pine or dead lodgepole, ln(DEAD), and the price escalation clause used in the timber sale contract (PMETH). These characteristics indicate the number and quality of the logs, and the contractual agreement of the sale. The standardized discriminant coefficients conclude that the STUMPMILL variable is the most important factor in determining sold and unsold sales, with SPLT second.

Table 7b presents the classification results for the eastside equations. The discriminant function correctly classified 90.0 percent of the timber sales, 92.9 percent of the unsold sales, and 88.5 percent of the sold sales. The holdout method indicates that the above classification results are unstable. The overall correct classification decreases to 72.5 percent, with 71.4 percent for the unsold sales and 73.1 percent for the sold sales. The logistic regression correctly classified 85.0 percent of the timber sales, with 71.4 percent correct classification for the unsold sales and 92.3 percent for the sold sales.

With the introduction of the gate 4 information, the equations have improved the overall classification results by 6.3 percent for the logistic regression and 16.1 percent for the discriminant equation.

WESTSIDE EQUATIONS

At gate 4, all information from the Gates timber sale planning process plus market information found in other sources is used to develop the equations. Given this fact, these equations are the most complicated. This has led to an equation that produces the most accurate prediction of salability.

The gate 4 equations are displayed in table 8. One should examine these equations from the standpoint of which variables have a positive effect and which have a negative effect on salability. The following variables have a positive effect on salability: the selling price (SPLT), the ratio of haul distances to primary and secondary appraisal points (HAULRAT), whether the contract follows the WWPA price index or remains fixed (PMETH), whether the mill site is competitive (COMPMILL), the 12-month percentage change in lumber production in the Intermountain zone (LMBRPROD), the volume-per-acre harvested (VPA), and the ratio of harvested acres to sale acres (DENSE). In general, the above characteristics indicate that a sale is likely to be sold: when composed

Table 8—Gate 4 westside equations and classification results

A. Equations

Variable	Logistic regression Coefficient	(Std Err)	Discriminant analysis Coefficient	(Std Coeff)
Ln(STUMPMILL)	–5.308	(0.716)	–3.307	(0.830)
$(SPLT)^2$	.00002	(.0000)		
Ln(SPLT)			.824	(.194)
Ln(HAULRAT)	.648	(.248)		
HAULRAT			.744	(.173)
DEAD	–.036	(.012)	–.023	(.270)
Ln(DENSE)			.183	(.148)
$(VPA)^{1/2}$			.113	(.150)
Ln(ACRES)			–.114	(–.137)
$(\%CABLE)^2$	–.00018	(.00004)	–.0001	(.487)
$Ln(UNCUT_{t-3})$	–9.340	(3.632)		
$(UNCUT_{t-3})$			–.0006	(.149)
COMPMILL	.864	(.288)	.636	(.318)
PMETH	.924	(.406)	.593	(.218)
LMBRPROD	.026	(.010)		
$EXCH_{t-3}$	–5.964	(3.124)	–6.856	(.419)
Constant	110.470	(28.442)	23.213	

B. Classification results

Actual group	Total sales	Logistic regression Correct predict	Percent correct	Discriminant analysis Correct predict	Percent correct
Unsold	145	100	69.0	115	79.3 (78.6)[1]
Sold	204	170	83.3	157	77.0 (75.0)[1]
All sales	349	270	77.4	272	77.9 (76.5)[1]

[1]Indicates percent correctly classified using the holdout method.

of higher valued species, located near several competitive milling centers, sale contract allows the winning bid price to fluctuate with the lumber market, lumber markets in an upswing, high volumes per acre harvested, does not require undue movement of harvesting equipment and labor.

As they rise in value, or are present in the timber sale the following variables negatively influence salability: stump-to-mill costs (STUMPMILL), percentage volume dead white pine or dead lodgepole (DEAD), percentage volume cable yarded (%CABLE), U.S./Canadian exchange rates ($EXCH_{t-3}$), and the uncut volume under contract ($UNCUT_{t-3}$) for the westside National Forests of Region 1. Once again these variables indicate sale quality in terms of costs and the type of volume harvested. The most important characteristic in determining salability is STUMPMILL, with %CABLE second.

Overall correct classification is approximately 78 percent (table 8b). The logistic regression correctly classified 69 percent of the unsold sales and 83.3 percent of the sold sales. The discriminant function correctly classified 79.3 percent of the unsold sales and 77.0 percent of the sold sales. The holdout method indicates that the discriminant function's classification results are stable.

Adding gate 4 and market information allowed the overall correct classification to increase approximately 12 percent. In addition to the overall improvement in correct classification, the gate 4 equations improved individual class results. Therefore we not only gain overall classification accuracy, but also accuracy within individual groups.

Statistical Evaluation

Up to this point I have discussed the classification results achieved when modeling sold and unsold timber sales at different gates, by different classification techniques, and by geographical zones. But the question still remains as to the statistical significance of the classification results achieved by the gates, classification technique, and geographical zone. The practical significance of the results are left to the reader to determine.

In general, the categorical analysis of variance (see table 9) indicates that a statistically significant difference exists in classification results when considering the geographical zone (eastside vs. westside), and when moving from gate 1 to gate 4. But there was no statistically significant difference in classification success with respect to the classification method (logistic regression vs. discriminant analysis). Also, there were no statistically significant interaction terms in the analysis of variance equation.

A statistically significant improvement in classification results was observed when moving from gate 1 through gate 4. As better information is used in the equation development process, the classification results improve significantly. The sale can be described in terms of average elevation, average slope, total volume, and sale acres at gate 1. These measures indicate the type of yarding systems that will be needed and the general size of the sale, but the general nature of the information will not allow an accurate model to be developed. The process needs specific information with regard to the percentage of volume cable yarded, the miles of road construction, the number of pieces moved, and so forth. Also, the equation is improved as market information is added to the process.

The results show that a statistically significant higher percentage of sales were correctly classified in the eastside National Forests. In general, the eastside equations had fewer variables than the westside equations.

Table 9—Categorical analysis of variance results[1]

Source	df	Chi–square	Probability
Intercept	1	2803.82	0.0000
Region[2]	1	10.16	[3].0014
Gate[4]	2	27.51	[3].0000
Method[5]	1	.08	.7724

[1]Interaction terms were not significant.
[2]Variable that represents the eastside and westside geographical zone.
[3]Indicates a statistically significant factor.
[4]Variable that represents gates 1, 2-3, and 4.
[5]Variable that represents the statistical methods.

But the simpler eastside equations correctly classified a higher percentage of the timber sales.

It is reassuring to know that as we add more specific information to the process, moving from gate 1 to gate 4, the classification results improve.

Also, having nonsignificant results with respect to the statistical procedure chosen is reassuring.

Classification Results and Cutoff Points

The classification results presented were based on a decision rule that assigns timber sales to the unsold category if the probability is less than 0.50, and to the sold category if greater than or equal to 0.50. As discussed earlier, one would expect classification results to change as the cutoff points (decision rules) are altered. Figure 1 presents the classification results based on the seven cutoff points defined earlier. When examining the eastside discriminant function (fig. 1), the most striking feature of gate 1 is the large fluctuation in the percentage correctly classified as the probability is varied. If the decision rule establishes that a predicted probability of 0.20 or greater defines a sold sale, the percentage of the sold sales that are correctly classified by the eastside gate 1 discriminant function is 100 percent. The tradeoff, however, is that under that rule, 0 percent of the unsold sales were correctly classified. At the other end of the scale, where a probability of 0.80 or greater defines a sold sale, the percentage of the sold sales correctly classified is 7.7; and the percentage of the unsold sales that are correctly classified is 100. The eastside gate 4 discriminant function at a predicted probability of 0.20 correctly classifies 64.3 percent of the unsold sales and 96.2 percent of the sold sales. At a probability of 0.80 sold, the classification results are 100 percent for unsold sales and 65.4 percent for sold sales. Figures corresponding to the other equations and gates are presented in appendix A, figures 2-4.

Figure 1 also illustrates how the cutoff points could be varied from gate to gate. As the timber sale nears the auction date, the land manager can become more precise regarding the cutoff point without drastically affecting the percentage correctly classified. At gate 1, which is 5 to 10 years from the auction date, the land manager may want to maintain the standard cutoff, 0.50.

The gate 1 equations produce the largest variation in percentage correctly classified at the various probability levels. The explanation is that gate 1 equations are the least accurate in percentage correctly classified. The gate 1 predicted probabilities are clustered around 0.50, meaning the equations have difficulty making correct predictions. As more and better information is generated (moving from gate 1 to gate 4), the equations are better able to classify sales, and the predicted values do not cluster around 0.50. For the eastside gate 1 discriminant function using a probability of 0.20, the percentage correct varies from 0 to 100; at a probability of 0.80 the percentage correct ranges from 100 to 7.7 for unsold and sold sales, respectively. The eastside gate 4 discriminant function ranges from 64.3 percent to 96.2 percent for a probability of 0.20, and 100 percent to 65.4 percent for a probability of 0.80. The maximum range for gate 4 is 34.6 percent, in comparison to 100 percent for gate 1.

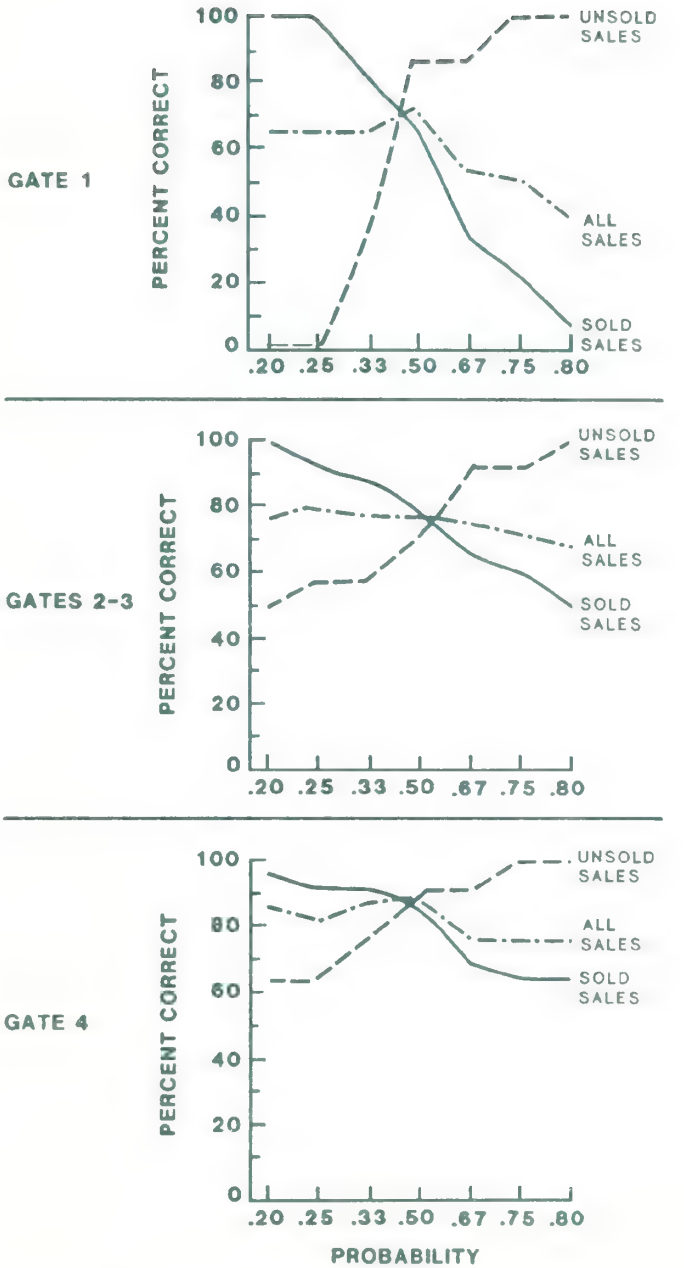

Figure 1—Cutoff point analyses for eastside Discriminant model.

MANAGEMENT IMPLICATIONS

The Gates timber sale planning system plays an important role in timber management. The Gates process can be viewed as adding structure to the designing of timber sales, where a sale must meet certain requirements before moving to the next gate. Additional information can be generated through the Gates process to help timber sale planners to make sound economic decisions about the

direction and extent of development. This is especially important today when government spending is a major issue. Using classification procedures, like those developed in this paper, coupled with the Gates process, the timber sale planner can generate a critical piece of information—likely salability. The planner must be aware of how his planning decisions affect salability.

The sale planning process starts with a timber management specialist inspecting a proposed sale area. Based on initial site and volume estimates, the forester determines if the area can support a timber sale. From a modeling standpoint, the volume estimates and site information can be used to assess salability.

At gates 2 and 3, the sale takes on more definite form, and more specific information is known about the prospective sale. It is now possible to more reliably evaluate salability. Using the more specific information, prediction capability of classification procedures has been improved. The ability to quantify sale design decisions, such as adding another mile of road or decreasing the volume per acre harvested, is essential to predicting salability. The prediction of salability is most important at this point. If salability can be accurately predicted at this point, the timber sale planner can implement the necessary changes to produce a salable offering.

Gate 4 offers little time to make necessary changes to produce a viable timber sale, with the auction only 3 months away. If selling the offering is questionable, the sale could be delayed and the necessary changes implemented to produce a salable timber offering.

The logistic regression and discriminant function were evaluated as salability classification tools. The categorical analysis of variance results verified that there was no statistically significant difference in prediction results with respect to the classification procedure.

But the logistic regression approach may have an added advantage over discriminant analysis. The logistic regression produces an estimated probability of a sale selling. This prediction supplies more information to the user about the degree of salability. For example, if the logistic model predicts a 10 percent chance of selling, this should indicate to the planner that major renovations are needed. The above sale is accurately classified as an unsold sale, but it is very different from a sale that might have an estimated probability of 0.45 (45 percent chance of selling). Given our 50-50 decision rule, they would both be classified as unsalable sales, even though the sale with an estimated probability of 0.10 should probably not be offered, while the other could be offered under favorable market conditions. The predicted probability provides the planner with a flexible decision rule. This flexibility could lead to a rule that allows for a zone of indecision. The zone could be defined as any sale having a probability less than 0.30 will be deferred, greater than 0.30 will be revised, and any sale having a probability greater than 0.70 will be advertised for sale. Any sale having an estimated probability falling in the 0.30 to 0.70 range of indecision will be withheld, revised, or advertised based on the professional judgment of the planning staff.

The equations described here were based on a sample of sold and unsold timber sales in the Northern Region of the Forest Service, during 1980 to 1985. The results should not be used to predict sold and unsold sales in any other region of the Forest Service nor for any other seller of stumpage.

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APPENDIX A: CUTOFF POINTS

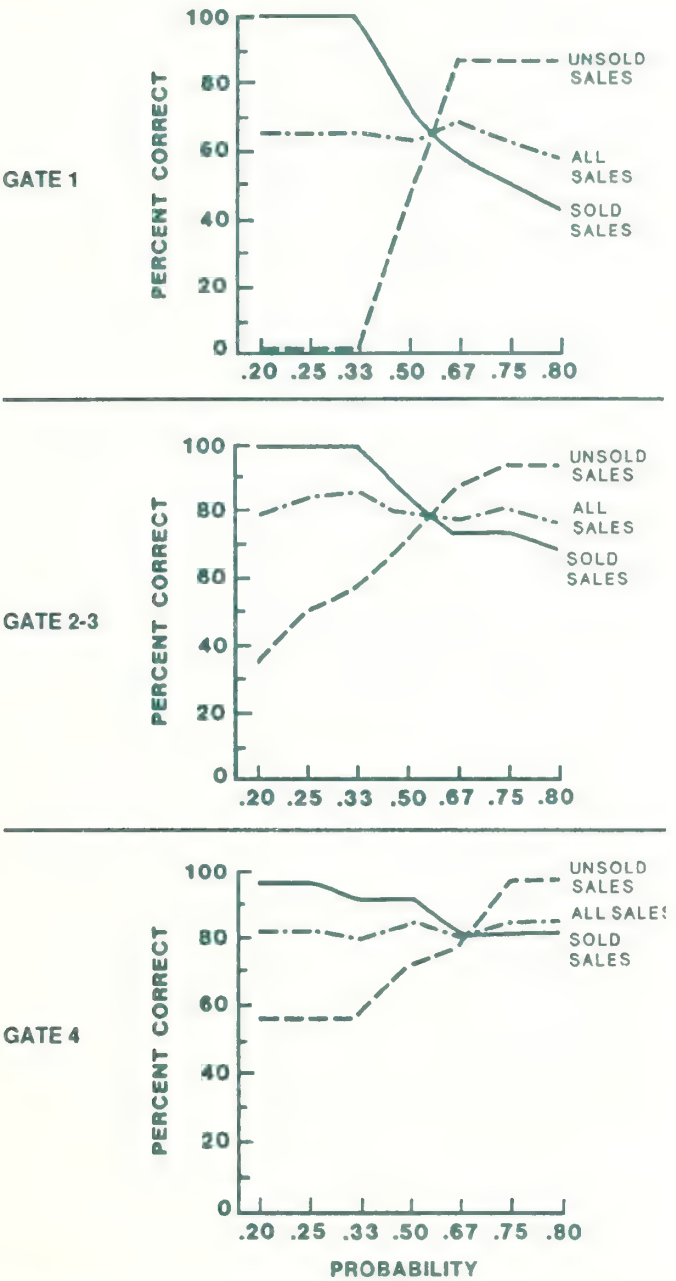


Figure 2—Eastside logistic regression model.

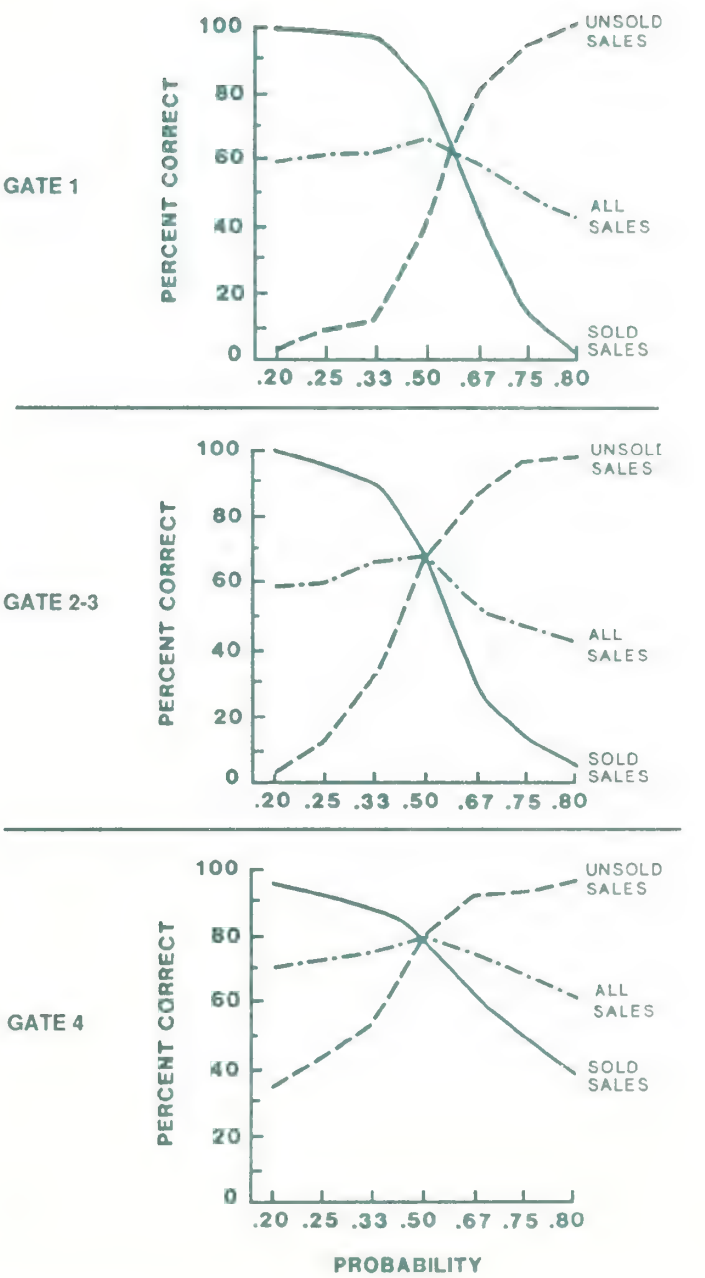


Figure 3—Westside discriminant model.

APPENDIX A (Con.)

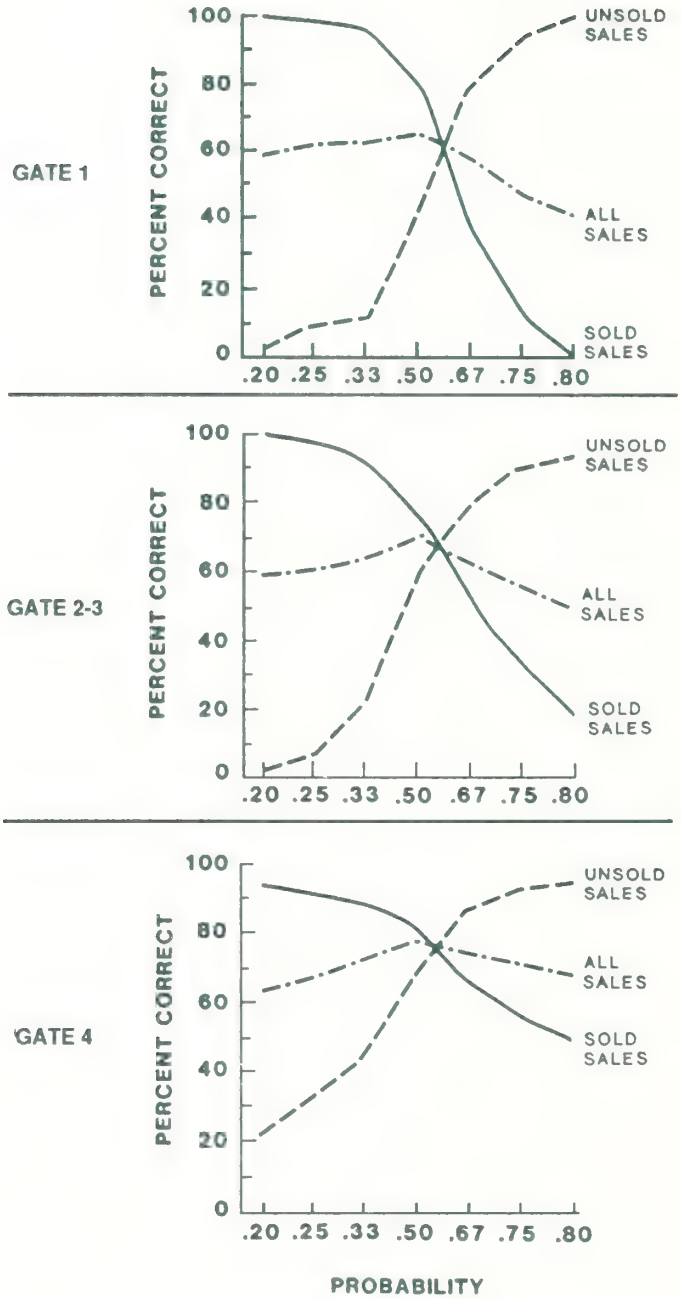


Figure 4—Westside logistic regression model.

APPENDIX B: DISCRIMINANT ANALYSIS CLASSIFICATION EQUATIONS

Table 10—Gate 1 eastside classification functions

Variable	Unsold function[1]	Sold function[1]
$(TOTVOL)^{1/2}$	0.125	0.147
TOTSALE	–.00096	–.00072
Constant	–2.207	–3.379

[1]Decision rule:
Unsold value > Sold value —then—> Unsold prediction
Unsold value < Sold value —then—> Sold prediction.

Table 11—Gate 1 westside classification functions

Variable	Unsold function[1]	Sold function[1]
Ln(TOTVOL)	2.554	2.841
Ln(TOTSALE)	.553	.128
AVGSLOPE	.140	.109
Constant	–14.486	–12.972

[1]Decision rule:
Unsold value > Sold value —then—> Unsold prediction
Unsold value < Sold value —then—> Sold prediction.

Table 12—Gate 2-3 eastside classification functions

Variable	Unsold function[1]	Sold function[1]
$(TOTVOL)^{1/2}$	–0.056	0.062
Ln(ALPM)	48.414	46.825
$(TOTROAD)^{1/2}$	–1.139	–2.965
Constant	–81.956	–78.007

[1]Decision rule:
Unsold value > Sold value —then—> Unsold prediction
Unsold value < Sold value —then—> Sold prediction.

Table 13—Gate 2-3 westside classification functions

Variable	Unsold function[1]	Sold function[1]
$(DENSE)^{1/2}$	19.399	20.392
$(VPA)^{1/2}$	3.019	3.398
$(NEW)^{1/2}$	–1.139	–2.965
$(RECON)^{1/2}$	.560	.523
Ln(DEAD)	.036	–.077
$(ALPM)^{1/2}$	4.611	4.398
(%TRAC)	018	035
Constant	–22.847	–24.577

[1]Decision rule:
Unsold value > Sold value —then—> Unsold prediction
Unsold value < Sold value —then—> Sold prediction.

Table 14—Gate 4 eastside classification functions

Variable	Unsold function[1]	Sold function[1]
Ln(STUMPMILL)	46.431	33.289
$(TOTVOL)^{1/2}$	–.136	–.056
Ln(SPLT)	317.393	331.734
Ln(ALPM)	–81.956	–78.007
Ln(DEAD)	2.579	3.197
PMETH	–30.205	–31.641
Constant	–1,011.769	–1,016.721

[1]Decision rule:
Unsold value > Sold value —then—> Unsold prediction
Unsold value < Sold value —then—> Sold prediction.

Table 15—Gate 4 westside classification functions

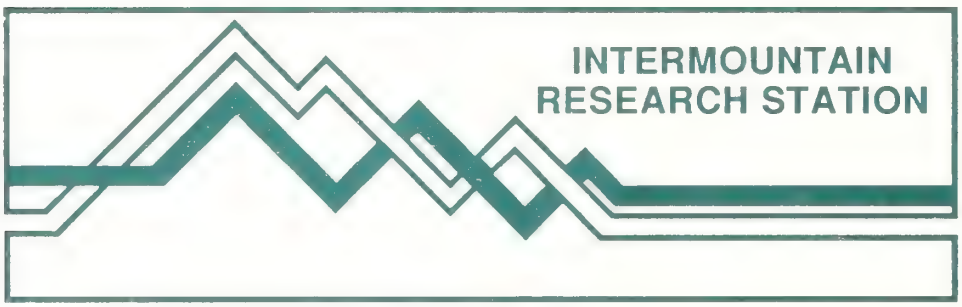
Variable	Unsold function[1]	Sold function[1]
Ln(STUMPMILL)	105.432	100.952
Ln(SPLT)	155.338	156.482
HAULRAT	17.254	18.292
DEAD	.366	.334
Ln(DENSE)	–4.533	–4.288
$(VPA)^{1/2}$	8.346	8.498
Ln(ACRES)	5.491	5.335
$(\%CABLE)^2$	–.00091	–.0011
$UNCUT_{t-3}$	.049	.048
COMPMILL	–8.184	–7.315
PMETH	–27.697	–26.897
$EXCH_{t-3}$	568.198	559.344
Constant	–1,170.096	–1,139.000

[1]Decision rule:
Unsold value > Sold value —then—> Unsold prediction
Unsold value < Sold value —then—> Sold prediction.

Niccolucci, Michael J. 1989. Predicting salability of timber sale offerings in the Forest Service Northern Region. Res. Pap. INT-418. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 13 p.

Some 389 sold and unsold timber offerings in the Northern Region of the Forest Service were used to develop classification equations. Equations were designed to be used at three points in the Gates timber sale planning process. Classification results ranged from 59 to 90 percent correct classification.

KEYWORDS: unsold timber sales, classification, Gates timber sale planning process, logistic regression, discriminant analysis



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Soil Chemical Properties of Raised Planting Beds in a Northern Idaho Forest

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RESEARCH SUMMARY

Forest soil productivity can deteriorate after harvest and site preparation as a result of changes in the physical, chemical, and biological environments. Nutrient depletion, especially nitrogen, is a major concern. The purpose of this study was to evaluate the planting bed (mound) as a means of enhancing early seedling survival and growth. Surface organic matter and mineral soil were mounded mechanically to form raised planting beds on two widely different habitat types. Soil nutrient concentrations of planting beds were compared to both scalped and undisturbed treatments on both sites. Total N, total P, pH, exchangeable Ca, Mg, and K were measured at the beginning of the growing season. Mineralizable N, ammonium, and nitrate were measured four times during the growing season. Seedling growth and nutrient content were evaluated at the end of the first growing season.

Total N, total P, and exchangeable cation concentrations were generally improved by mounding, although not always significantly ($P \leq 0.05$). A similar trend was true for available nitrogen concentrations. Nitrogen fluctuated throughout the growing season, but the scalped treatment had lower concentrations than either mounded or undisturbed soils. Soil nutrient concentrations were directly correlated with organic matter content of the treated soil. Organic residues also acted as a mulch to retain soil moisture and improve aeration.

First-year seedling response to the treatments was minimal because of nutrient carryover from the greenhouse production environment. At both sites, however, seedling total N was greater in the mounded and undisturbed treatment than in the scalped treatment. High N concentrations will likely benefit both short- and long-term seedling performance and overall site productivity.

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INTRODUCTION

Future productivity of forested sites in the Inland Northwest may be reduced through more intensive harvesting and increased mechanization. Productivity of forest stands is largely dependent on favorable soil physical, chemical, and biological properties. But forest operations like harvesting entail a high risk to all of these soil properties (Reisinger and others 1988). In many stands where whole tree harvesting is commonplace, nutrient depletion is a concern (Johnson 1983; Weetman and Webber 1972). Direct loss of nutrients from harvesting and site preparation occurs after removal of stems, branches, and twigs. In addition, nutrient losses through increased leaching to groundwater sources and erosion are major concerns to site recovery after harvesting (McColl and Grigal 1979).

It is common to use some type of site preparation after harvest to ensure adequate mineral soil exposure, seed germination, and early survival, or to reduce nonconifer, competitive vegetation (Morris and Lowery 1988). In the Western States, mechanical methods (scalping) or burning are used to prepare sites for both natural and artificial regeneration. Most often, these methods are used together, primarily to remove competing sprout vegetation (Stewart 1974). In contrast, forest management in the Gulf States has relied on site preparation by chopping, disking, and bedding for successful plantation establishment (McMinn 1969; Wilhite and Harrington 1965; Worst 1964). From a soils point of view, the aim of all these site preparation techniques is to ameliorate the physical properties of cutover sites by increasing the pore space (Shoulders and Terry 1978), by improving aeration and moisture availability (Hite 1976; Pritchett 1979), or by decreasing soil resistance to root penetration (Fox 1977; McKee and Shoulders 1974).

One benefit of forming the soil into planting beds is the concentration of nutrients at the planting microsite. Gutzwiler (1976) noted that the highest concentrations of nitrogen (N) and phosphorus (P) were found in the top mineral layer and organic matter of the forest floor. Organic matter concentrations are as much as one-third to one-half higher in mounded soil than in scalps (Pritchett and Wells 1978; Shultz and Wilhite 1974). Organic matter mixed with soil and mounded by bedding equipment decomposed quickly and released substantial quantities of nutrients. The accelerated decomposition of organic matter in mounds was also cited by Pritchett and Wells (1978) as a provider of nutrients for seedling growth and early establishment. Haines and Pritchett (1965) attributed increased growth of southern pine seedlings after bedding to this nutrient release. Mounding significantly increases calcium (Ca), magnesium (Mg), and potassium (K) (Shultz and Wilhite 1974), and also N and P concentrations (Attiwill and others 1985) at various depths in treated soil profiles.

Most work with soil mounding has been done on wet lowland sites. But in a few cases (Francis 1979; Frederick and others 1983; Gilmore and others 1968), mounding has been successful in improving tree growth and vigor on upland sites. Mounding also can ameliorate undesirable soil physical properties and can increase moisture and nutrient availability. The forming of beds by mounding surface organic matter and mineral soil has been shown to improve both physical properties and moisture retention of several soils in northern Idaho (Page-Dumroese and others 1986). This study compares the changes in important soil chemical properties brought about by mounding or scalping of two cutover sites in northern Idaho, and subsequent effects on first-year outplanted seedlings.

STUDY DESCRIPTION

The objective of this study was to compare raised planting beds with conventional site preparation treatments, both in terms of soil chemical properties, including total N, total P, pH, exchangeable cations (Ca, Mg, K), ammonium and nitrate levels, nitrogen mineralization potential, and first-year seedling growth response. This study was conducted on two productive habitat types with distinctively different regeneration problems. These two sites, located at differing elevations, provided a range of environmental conditions for evaluating the effectiveness of bedding as a means of ameliorating soil disturbance-related hazards to seedling survival, and performance in forest soils of the Inland Northwest.

SITE DESCRIPTION

Two sites, located on the Priest River Experimental Forest near Priest River, ID, were used in this study. The Experimental Forest lies on the westward slope of a spur of the Selkirk Mountains in northwestern Idaho.

One site is located at an elevation of 715 m above sea level on a flat bench adjoining the Priest River. It is the warmer and drier of the two sites, has the longer growing season, and is considered the harsher of the two sites. Burned in 1922, this site had been used as an area for studying flammability of forest fuels and was occupied by grasses, forbs, and a few lodgepole pine (*Pinus contorta* Dougl. ex Loud.). The soil is a coarse, loamy, mixed frigid Typic Xerochrept. The habitat type is classified as *Abies grandis / Symphoricarpos albus* (Cooper and others 1987). Annual precipitation averages 83.8 cm, with a mean annual temperature of 6.6 °C (Wellner 1976).

The second site is at an elevation of 1,456 m above sea level near Observatory Point in the Canyon Creek watershed. Slopes range from 10 to 35 percent and have north-to-northeast aspects. The soil is classified as a coarse, loamy, Typic Cryorthent; the habitat type is *Tsuga heterophylla / Clintonia uniflora* (Cooper and others 1987). This study area consisted of a mixed stand of western hemlock (*Tsuga heterophylla* [Raf.] Sarg.), grand fir (*Abies grandis* [Dougl. ex D. Don] Lindl.), and western white pine (*Pinus monticola* Dougl. ex D. Don). This is a highly productive forest site with stand volume increases of 8 m^3/ha/yr. It was clearcut and the slash piled and burned in the fall of 1981. Annual precipitation at this elevation averages 92.3 cm, and the mean annual temperature is 5.3 °C (Wellner 1976).

STUDY DESIGN

Both sites were mechanically prepared in the summer of 1982, and a randomized complete block experiment established at each site. At the low-elevation site, there were four treatments with four replications in one large block. The high-elevation site consisted of four treatments with three replications. It was divided into three separate 1-ha cutting areas having approximately the same slope, aspect, soil, and habitat type.

The treatments on these sites consisted of: (1) mounded soil beds with competing vegetation not removed, (2) mounded soil beds with competing vegetation removed manually in June and July, (3) a scalped area wherein the top 10 cm of organic matter and mineral topsoil were removed, and (4) an area essentially undisturbed after harvesting. Each treatment was approximately 30 m long and, for the mounded treatments, approximately 46 cm high. In May, the treatments were planted with locally adapted, container-grown Douglas-fir on a 1- by 1-m spacing.

Soil Sampling and Analysis

Soil samples were taken from each treatment four times during the growing season. Samples were collected from 15 randomly selected sites in each treatment replication, to a depth of ca. 30 cm; the approximate maximum depth of seedling roots at the end of the first growing season. All soil samples were passed through a 2-mm sieve and dried before analysis. Organic matter was determined by weight loss after combustion at 375 °C for 16 hours (Ball 1964). Soil total N and total P were analyzed by the Kjeldahl digestion method using the salicylic acid-sodium thiosulfate modification (Bremner and Mulvaney 1982) and assayed on a Technicon Auto Analyzer II. Soil exchangeable Ca, Mg, and K were extracted using 1*N* NH_4OAc and analyzed by atomic absorption techniques (Page 1982). Nitrogen mineralization was estimated using the anaerobic incubation technique (Powers 1980). Nitrate and ammonium contents were determined on 1*N* KCl extract using a Technicon Auto Analyzer II. Soil acidity was determined on a 2:1 water:soil mixture. Soil nutrient concentrations were corrected to reflect average rooting depths of seedlings in each treatment.

Foliage Sampling and Analysis

Entire seedlings were excavated and dried at 60 °C for 24 hours. Total root and top weight and top height were measured. Stems and foliage were analyzed together. Total N and total P were analyzed by Kjeldahl digestion methods using the salicylic acid-sodium thiosulfate modification (Bremner and Mulvaney 1982) and assayed on a Technicon Auto Analyzer II. Foliage samples for Ca, Mg, and K were dry ashed, extracted with 2*N* HNO_3, and assayed by atomic absorption techniques (Thomas 1982).

An analysis of variance was conducted on the data using a randomized complete block design. Treatment means were separated using Scheffe's multiple range test. All foliage and soil chemical analyses included sets of blanks, duplicates, and standard reference materials. Soil data from the two mounded treatments (with and without competing vegetation) were combined because (on each site) there were no significant differences in nutrient concentrations between them.

RESULTS AND DISCUSSION

Soil Properties

Mounded treatments had significantly higher organic matter levels ($P \leq 0.05$) than scalped treatments (table 1), but were not significantly different from the undisturbed treatment. Most of the forest floor remained intact on the undisturbed treatment, while the scalp treatment removed a significant portion of organic matter from the soil surface.

Table 1—Soil organic matter content (percent) and rooting zone depth (cm) as affected by site treatment. Different letters indicate significant differences ($P \leq 0.05$) among treatments

Treatment	Low elevation		High elevation	
	O.M.	Root depth	O.M.	Root depth
	Percent	*cm*	*Percent*	*cm*
Mounded	15.0a	24.5a	27.5a	23.8a
Scalped	9.4b	20.8b	14.5b	19.7c
Undisturbed	14.4a	20.9b	29.2a	20.6b

Table 2—Average year-end total and available nitrogen concentration, total phosphorus content, and pH as affected by site treatment. Different letters indicate significant differences ($P \leq 0.05$) between treatments

Treatment	Total N	Total P	NH_4	NO_3	Mineralized N	pH
	Percent		*mg/kg*			
Low elevation:						
Mounded	0.03a	0.27a	1.3a	1.3a	5.4a	5.7a
Scalped	.01a	.22a	.8ab	1.0a	.5a	6.1a
Undisturbed	.03a	.24a	.5b	.9b	1.7a	6.0a
High elevation:						
Mounded	.07a	.11a	10.1a	6.1a	47.7a	5.4a
Scalped	.03a	.07a	.5a	1.2b	3.8b	5.5a
Undisturbed	.03a	.12a	4.3a	4.9a	43.5a	5.4a

Soil acidity (pH) did not reflect site preparation treatment of the topsoil (table 2). But there were differences between sites, with the low-elevation site having a higher pH than the high-elevation site. This difference was likely caused by a combination of base cycling from the grasses present at the low site and the high decayed wood content of the soil at the high-elevation site.

Mounding consolidated woody materials and organic matter in the root zone and thereby raised soil nutrient levels. More total soil N was found at the high-elevation site than at the low site. Total N content increased as a result of the mounding process (table 2), although these differences were not significant among treatments due to high within-site variability. Scalping to remove topsoil and organic matter resulted in less total N. Losses up to 50 percent of N storage have been suggested by Morris and others (1983) in the southeastern United States. Available soil nitrogen levels were also higher in the mounded treatment (table 2).

The soil N mineralization potentials following each site treatment at four times during the growing season are shown in figures 1 and 2. At the low-elevation site in particular, potential N release from the soil was greatest after mounding. At both sites, scalping the soil had adverse effects on N mineralization. Other investigators have also shown that mechanical site preparation techniques that remove the topsoil reduce the N mineralization potential (Burger and Pritchett 1984; Fox and others 1986). Nitrate levels followed similar seasonal and treatment trends (figs. 3 and 4) and, as with nitrogen mineralization potential, the high-elevation site had higher N levels than the low-elevation site. This is probably a function of the relatively large quantity of organic matter at the high-elevation site. Ammonium concentrations (table 2) also followed these trends.

The mounded treatment slightly increased total P concentration through the mixing of organic matter. In contrast to N results, total P values were lowest at the high-elevation site (table 2). Since total P may be increased through addition of fresh vegetation (Alexander 1977), the higher values at the low elevation can be associated with the incorporation of grasses into the mounds.

Differences in exchangeable cations followed trends similar to the other nutrients at the low-elevation site (table 3). But this pattern was much weaker at the high-elevation site. Base concentrations were high in the scalped soil, although the differences among treatments were not significant. Similar results were reported by Shultz and Wilhite (1974). They also reported that mounding increased Ca, Mg, and K concentrations in the rooting zone.

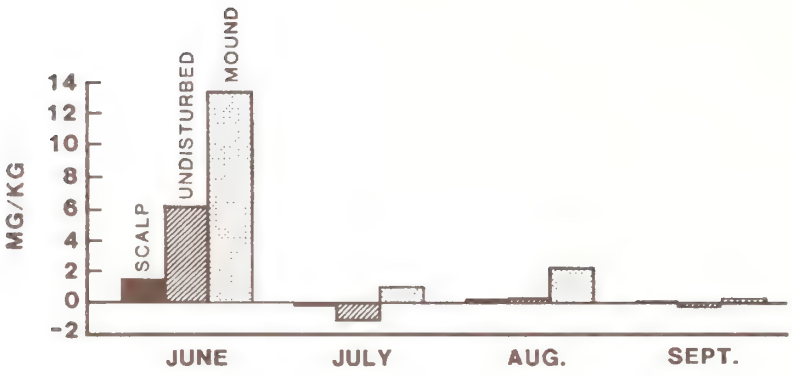

Figure 1—Treatment vs. mineralizable N potential for the low-elevation site.

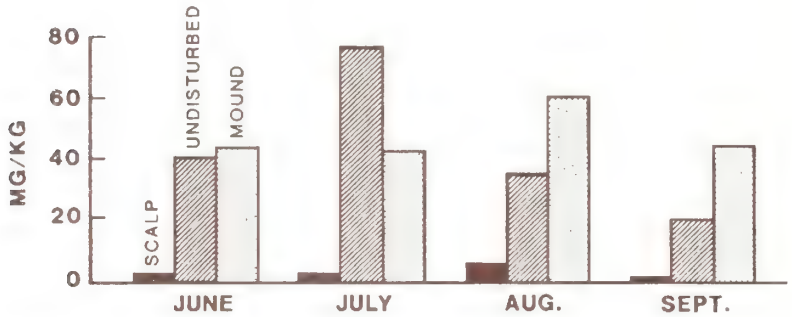

Figure 2—Treatment vs. mineralizable N potential for the high-elevation site.

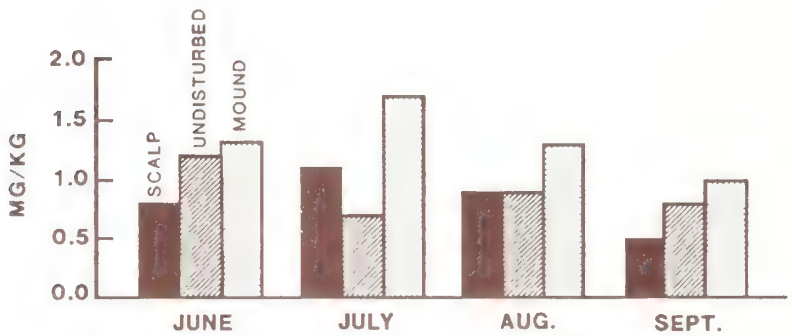

Figure 3—Treatment vs. nitrate levels for the low-elevation site.

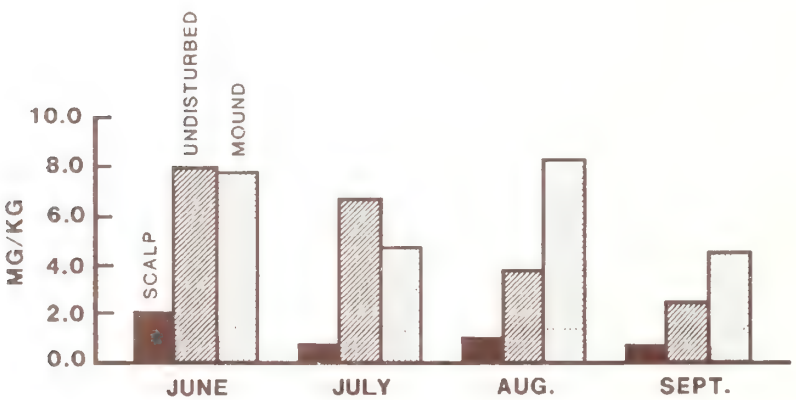

Figure 4—Treatment vs. nitrate levels for the high-elevation site.

Table 3—Average year-end cation concentration as affected by site treatment. Different letters indicate significant differences ($P \leq 0.05$) between treatments

Treatment	Low elevation			High elevation		
	Calcium	Magnesium	Potassium	Calcium	Magnesium	Potassium
	mg/kg			mg/kg		
Mounded	12.3a	3.7a	5.1a	10.5a	3.0a	4.7a
Scalped	4.4a	1.2b	2.4a	9.9a	2.5a	6.4a
Undisturbed	7.7a	1.9ab	3.3a	4.9b	2.6a	2.3a

Table 4—Average first-year physical and chemical properties of Douglas-fir seedlings as affected by site treatment. Different letters indicate significant differences ($P \leq 0.05$) between treatments

Treatment	Height	Root weight	Top weight	Total N	Total P	Ca	Mg	K
	cm	g		Percent		mg/kg		
Low elevation:								
Mounded	15.6a	8.2a	15.1a	0.13a	0.28a	467a	160a	946a
Scalped	15.0a	6.9ab	13.9a	.08b	.26a	479a	156a	890a
Undisturbed	15.5a	6.5b	14.3a	.11ab	.31a	512a	184a	1,062a
High elevation:								
Mounded	17.2a	7.3a	12.7a	.130a	.33a	469a	153a	941a
Scalped	15.2a	7.9a	10.9a	.072b	.29a	427a	160a	754a
Undisturbed	15.0a	6.8a	11.3a	.133a	.33a	422a	175a	929a

Seedling Properties

Rooting depth was significantly affected by mounding. At both elevations Douglas-fir seedlings in the mounded treatment had significantly greater rooting depth than those planted in undisturbed or scalped soil treatments. This may be due to the low bulk density and improved aeration (Page-Dumroese and others 1986). Seedlings grown at the low-elevation site in the undisturbed and the scalped treatment did not differ significantly from each other in rooting depth. At the high-elevation site, scalping significantly reduced rooting depth as compared to the undisturbed treatment. This is most likely associated with high bulk densities after scalping (Page-Dumroese and others 1986).

In general, seedling growth response to site treatment and nutrient uptake was not pronounced during the first growing season (table 4). Root weights were higher from the scalped treatment, but top weights were greater following soil mounding. At both sites total seedling N concentrations were higher for the mounded and undisturbed soil treatments. This likely reflects the increased availability of N in the mounded and undisturbed soils (table 2). Soil total P was greater at the low-elevation site, but seedling total P was slightly higher at the high-elevation site. This may reflect greater P mineralization rates at this elevation. First-year changes in other seedling nutrient uptake characteristics were not pronounced. This was not surprising, because outplanted seedlings usually have a store of nutrients in their buds and tissue from the nursery which greatly affects their first-year growth (Kozlowski and others 1973). But changes in soil properties adjacent to the root system may alter seedling uptake in subsequent years as roots begin growing outward.

CONCLUSIONS

Bedding had several favorable effects on the nutrient availability of two widely differing sites in northern Idaho. Organic matter levels were higher in the mounded treatment than the scalped treatment, which led to high microorganism activity and nutrient availability. Without adequate nutrient pools, long-term fertility problems can occur.

Total N, total P, Ca, Mg, K, and available N levels can be maintained by conserving organic matter after harvesting. Mounding increased nutrient concentrations in the root zone, but the undisturbed treatment also had substantial quantities of nutrients. The contrast between two sites used in this study illustrates that mounding, or at least an attempt to maintain organic matter, can create a very favorable environment for seedling growth.

After initial seedling establishment, the most important aspect of site preparation is the long-term growth effects. Removal of organic horizons severely limited N mineralization potential. Where initial N supplies are decreased, long-term N availability will also be reduced. This can lead to general declines in productivity. Conservation of organic matter is an important consideration when planning a harvest/site preparation sequence.

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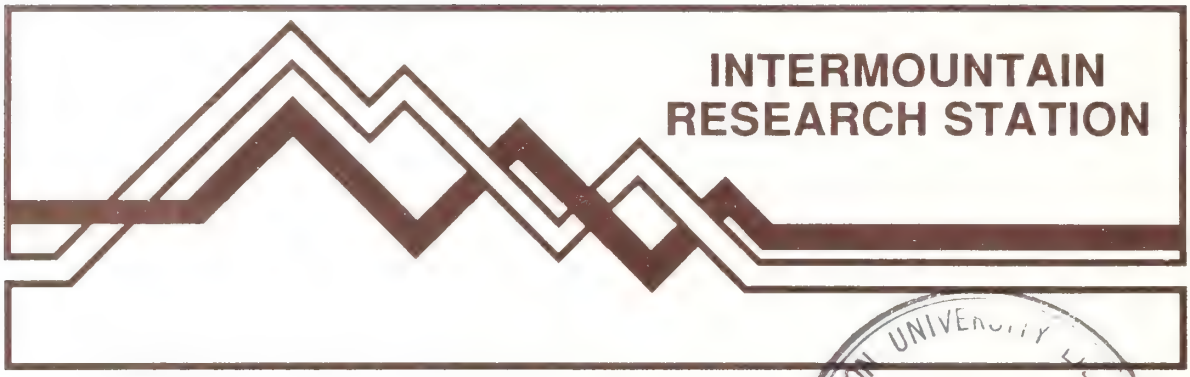
Mounded soil of mixed organic residues and mineral soil had higher concentrations of critical chemical components in seedling rooting zones when compared to scalped planting sites. Total N, total P, exchangeable Ca, Mg, and K, and available nitrogen were all improved by mounding. Improving chemical properties in planting beds (mounds) will likely enhance both survival and long-term growth of outplanted seedlings in many Inland Northwest soils. Although scalping increases early survival of conifer seedlings on sites with severe competition, reductions in both organic matter and nutrients, especially available nitrogen, may diminish site productivity over the long term.

KEYWORDS: site preparation, soil mounds, soil productivity, nutrient depletion



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Incidence of Compression Wood and Stem Eccentricity in Lodgepole Pine of North America

**Peter Koch
W. A. Côté, Jr.
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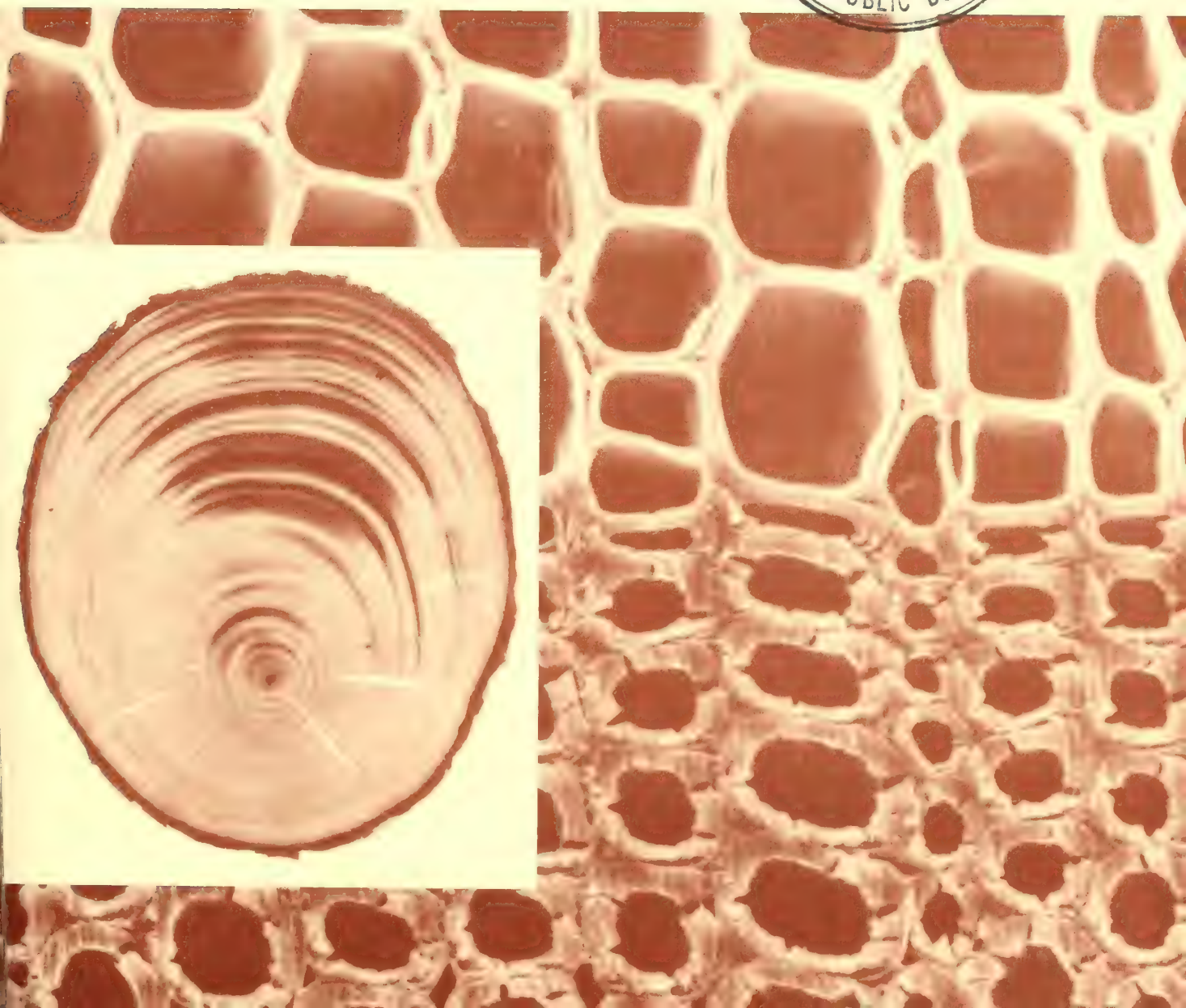

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RESEARCH SUMMARY

Although present in virtually all lodgepole pines, compression wood is extremely difficult to detect visually in log ends in a woods or mill environment. Of 243 *latifolia* trees sampled from 40° to 60° latitude, only one was free of compression wood; none of the 36 *murrayana* trees sampled from 37.5° to 45° latitude were free of compression wood. Trees 76 mm in d.b.h. of both varieties had significantly higher stem-average percentage of compression wood than those 152 mm or 228 mm in d.b.h. *Latifolia* trees had less compression wood (5.5 percent) than *murrayana* trees (7.7 percent). In both varieties, sections sampled from 45° through 50° latitude had the greatest proportion of sections free of compression wood.

Transverse stem sections typically display a compression wood pattern of one-sided eccentricity in which the main body of compression wood is opposite an eccentrically located pith, and along a line projected from pith through the center of the largest circle that can be inscribed in the section. Sections or short logs sampled from stems of both varieties tend to have high percentages of compression wood if they are out of round and close to ground level, and have eccentric piths, high specific gravities, and low moisture contents.

Stemwood averages most elliptical in cross section in trees from 57.5° and 60° latitude. Stemwood of both varieties is most nearly circular in cross section near midheight of trees.

Tree-average pith eccentricity averages 6.7 mm and does not differ between varieties. In *latifolia* it is smallest (5.5-6.3 mm) in the intermediate latitudinal zone from 45° to 52.5°, and is larger in more southerly and more northerly latitudes (6.8-8.0 mm).

RELATED PUBLICATIONS

Readers interested in further studying characteristics of lodgepole pine in North America related to its utilization should find useful the following books and papers tabulated by date of publication—each part of a series on the subject (see References for complete citations):

Citation	Subject
Burke (1985)	Anatomical variations of lodgepole pine in North America (study in progress)
Koch (1987a)	Gross characteristics of lodgepole pine in North America
Koch (1987b)	Spiral gram in stemwood of lodgepole pine in North America (study in progress)
Koch and Barger (1988)	Atlas of 28 selected commercial forest areas in the United States with unutilized stands of lodgepole pine
Koch and others (1989)	Proposed wood products plant to utilize sub-sawlog-size and dead lodgepole pine in northwestern Montana—a technical and economic feasibility analysis
Kim and others (1989)	Chemical variation in lodgepole pine with latitude, elevation, and diameter class
Kossuth and Koch (1989)	Stimulation of oleoresin flow in lodgepole pine lower stem and rootwood
Pellerin and others (1989)	Mechanical properties of lodgepole pine: 3-inch diameter stems
Pellerin and others (1989)	Mechanical properties of lodgepole pine: 6- and 9-inch diameter stems
Campbell and others (1990)	Chemical variation in lodgepole pine with sapwood/heartwood, stem height, and variety (includes ultimate and proximate analyses)
Wiedenbeck and others (in press)	Air permeability, shrinkage, and moisture sorption of lodgepole pine

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Incidence of Compression Wood and Stem Eccentricity in Lodgepole Pine of North America

Peter Koch
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A. C. Day

PROBLEMS INDUCED BY COMPRESSION WOOD

Timell (1986, p. 579) has succinctly summarized the problems related to utilization of compression wood:

> From a wood utilization point of view, compression wood has many drawbacks. Most serious is its high longitudinal shrinkage which causes warping and other distortions in lumber containing both normal and compression woods. Its second most serious disadvantage is its low ability to increase in strength on drying, which renders it weaker than normal wood not only in tension, which it is under all circumstances, but also in many properties related to compression and bending. A third drawback is the brash rupture characteristic of compression wood which, where it occurs in construction lumber, can render a danger to life and property. As a fourth disadvantage must be listed the great hardness of compression wood, which makes it difficult, if not impossible, to nail or work with ordinary tools.

While not emphasized by Timell in the above passage, modulus of elasticity—a critical property of structural wood—is very much less for compression wood than for normal wood. Since stiffness of structural wood members more frequently controls design than ultimate load, this deficiency is a serious shortcoming in compression wood. Also, compression wood has less alpha cellulose and more lignin than normal wood, characteristics adversely affecting its utility as pulpwood.

The problem faced by North American manufacturers of lodgepole pine products is that the literature affords no assessment (locally or rangewide) of the incidence of compression wood in the stemwood of the species, and hence manufacturers have no rationale for avoiding stems with excessive compression wood content; neither do they have a clear picture of its pervasiveness.

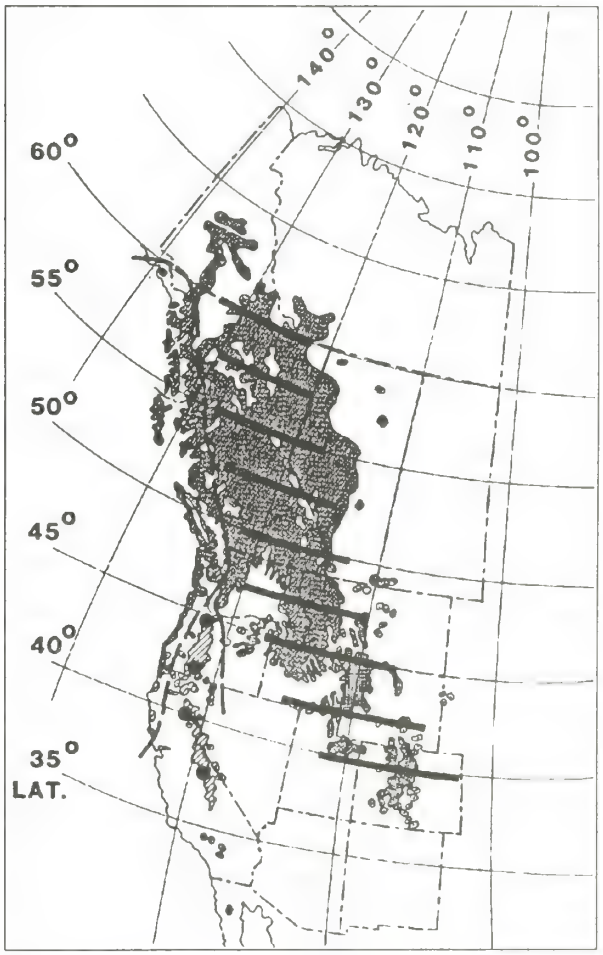


Figure 1—Sampling zones superimposed on Little's (1971) range map of lodgepole pine in North America. Variety *latifolia* is mapped to the right of the dashed lines, *murrayana* between them, and *contorta* to the left of them. Variety *contorta* was not studied because of its small potential for commercial use.

STUDY SCOPE AND OBJECTIVES

The purpose of this study was to ascertain the incidence of compression wood in the stemwood of the two principal varieties of lodgepole pine (*Pinus contorta* var. *latifolia* Engelm. and *Pinus contorta* var. *murrayana* [Grev. and Balf.] Engelm.) throughout their major ranges in North America (fig. 1), and to correlate this incidence with height in tree, degree of pith eccentricity, and stem out-of-roundness—and with other selected variables such as latitude, longitude, elevational zone, diameter at breast height (d.b.h.), tree height, magnitude of stem crook, stemwood specific gravity, average growth ring width at stump height, crown ratio, number of branches, average

branch diameter, stem taper, length of tap root, and proportions of complete-tree weight represented by roots, bark, stemwood, branchwood, and foliage.

The primary objective during tree collection was to obtain disease-free and insect-free specimens of 76-, 152-, and 228-mm (3-, 6-, and 9-inch) lodgepole pine (var. *latifolia*) at low, medium, and high elevations from nine equally spaced north latitudinal zones (40 to 60 degrees) across 10 degrees of longitude, in such a way as to encompass the major range of this variety (fig. 1).

A secondary objective during tree collection was to sample these same three diameter classes of var. *murrayana* at midelevation at four north latitudes (37½, 40, 42½, and 45 degrees) in California and southern Oregon at a single longitude per latitude (fig. 1).

The trees of both varieties were sampled in such a way that between-variety comparisons could be made for midelevation trees from latitudes 40, 42½, and 45 degrees. The collection totaled 243 *latifolia* trees and 36 *murrayana* trees.

See table 1 for summary information on these trees.

Table 1—Summary information descriptive of the 279 lodgepole pines in the study. Data averaged over full range of sample, by variety

Variable	Tree diameter at breast height		
	76 mm	152 mm	228 mm
***Latifolia* (81 trees of each diameter)**			
Age at 152-mm-high stump top, years	71	91	107
Height from 152-mm-high stump top to apical tip, meters	9.3	15.6	19.1
Taproot length measured from 152-mm-high stump top, centimeters	55	78	94
Average width of annual rings at 152-mm-high stump top, millimeters	0.7	1.0	1.3
Average diameter outside bark of live branches 50 mm from stem, millimeters	9	13	19
Average branch angle, degrees[1]	85	79	77
Ratio of live-crown length to tree height (crown ratio)	0.48	0.44	0.45
Number of live branches	64	108	133
Number of dead branches	57	100	119
Stem taper inside bark below live crown, millimeters per meter	6.3	7.8	10.5
Stem taper inside bark from base of live crown to apical tip, millimeters per meter	13.1	15.9	18.5
Stemwood-average moisture content, percent	99	100	98
Stemwood-average specific gravity[2]	0.43	0.42	0.41
***Murrayana* (12 trees of each diameter)**			
Age at 152-mm-high stump top, years	67	84	91
Height from 152-mm-high stump top to apical tip, meters	7.4	13.7	18.7
Taproot length measured from 152-mm-high stump top, centimeters	58	91	97
Average width of annual rings at 152-mm-high stump top, millimeters	0.7	1.1	1.6
Average diameter outside bark of live branches 50-mm from stem, millimeters	7	12	18
Average branch angle, degrees[1]	88	83	78
Ratio of live-crown length to tree height (crown ratio)	0.60	0.55	0.59
Number of live branches	72	127	146
Number of dead branches	34	79	94
Stem taper inside bark below live crown, millimeters per meter	5.8	10.8	11.9
Stem taper inside bark from base of live crown to apical tip, millimeters per meter	14.5	16.0	16.6
Stemwood-average moisture content, percent	98	114	121
Stemwood-average specific gravity[2]	0.48	0.44	0.41

[1]Angle between branch and stem; upward-pointing branches less than 90°; drooping branches more than 90°.
[2]Based on green volume and ovendry weight.

LIMITATIONS OF THE STUDY

A work of this scope, describing trees of a species with great latitudinal, longitudinal, and elevational range, cannot meet the needs of readers of all disciplines. Recognizing this reality, the work was written principally for use by industrialists, scientists, process engineers, and students who need a description of gross species characteristics and some appreciation of their variation within North America.

Because the sampling plan calls for a specimen collection stratified by d.b.h., latitude, and elevational zone—without sampling intensity adjusted for volume distribution within these stratifications—it does not permit computation of species-average values valid rangewide. Moreover, the sampling plan does not permit evaluation of effects of site quality, age, and stand density—even though it is well known that these three parameters significantly affect many, perhaps most, of the characteristics evaluated. This shortcoming in experimental design was thoroughly discussed before study initiation.

As resources available for this study of lodgepole pine as an industrial raw material were not only finite, but modest, the study objectives were limited to determination of broad material-characteristics variations related to tree d.b.h. and spatial location (latitude, longitude, and elevational zone). The study was not designed to deal with the very complex relationships involving site quality, tree age, or stand density; as a result, the sampling plan does not permit such analyses.

The elevational range of lodgepole pine (*latifolia*) is considerably greater in southern latitudes than in northern (fig. 2); and it is probable that site quality and stand densities vary less in northern than in southern latitudes.

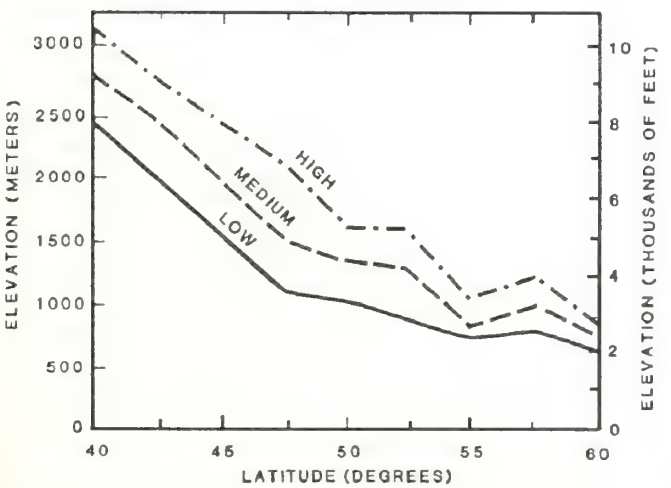


Figure 2—Elevational trends in the three zones (low, medium, and high) where lodgepole pine (var. *latifolia*) was sampled along nine latitudes. Each plotted point is the average for nine trees; that is, three diameters by three replications.

THE LODGEPOLE PINE RESOURCE IN NORTH AMERICA

To appreciate the scope of the work and to understand the rationale for the sampling design, it is useful to know something about the resource.

Lodgepole pine (*Pinus contorta* Doug. ex Loud.) occupies about 5¼ million ha of commercial forest land in the United States (containing 748 million m^3 of lodgepole growing stock and over 71 billion board feet of lodgepole timber, mostly in Montana, Idaho, Wyoming, Colorado, and Oregon), and is the fourth most extensive timber type west of the Mississippi River. On these 5¼ million ha, a significant proportion of the trees are dead, having been killed by insects. In the Northern Region alone, a 1979 survey reported 540,862 ha severely infested with mountain pine beetle. The most recent survey data for Idaho indicate that insects and disease have killed about 1 percent of the lodgepole pine trees. In Canada the acreage of lodgepole pine forest type (20 million ha, comprising 22 percent of the total forest land in western Canada) is greater than in the United States.

Most of the North American lodgepole pine resource is of the variety *latifolia* (*Pinus contorta* var. *latifolia* Engelm.) centered along the Rocky Mountains from 40 to 60 degrees north latitude, with Sierra lodgepole pine (*Pinus contorta* var. *murrayana* [Grev. & Balf.] Engelm. and shore pine (*Pinus contorta* Dougl. ex Loud. var. *contorta*) comprising significantly lesser volumes on Sierra and coastal areas (fig. 1). A fourth variety, *bolanderi* (Parl.) Vasey, is a shrub local in Mendocino County, CA.

In both Canada and the United States, much of the lodgepole resource is in older (60-200 years) virtually stagnated stands in which growth rate is very low and mortality very high. Typically trees are small in diameter. Slightly more than one-third of the volume (ovendry weight basis) is in trees less than 175 mm in diameter measured at breast height outside bark (Van Hooser and Chojnacky 1983); such a diameter might be considered the lower limit for lumber manufacture.

Silvicultural treatments (thinning or removal and regeneration to managed stand with controlled stocking) are so expensive, and stumpage revenue so little, much of the acreage has received no treatment to accelerate growth and slow mortality.

PAST AND CURRENT WORK

Timell's (1986) three-volume work on compression wood in gymnosperms is an up-to-date and thorough review of world literature on the subject. This section presents brief abstracts of some of Timell's conclusions regarding the physiology of compression wood formation, anatomical characteristics, chemical composition, knots and compression wood, and the mechanism of compression wood in righting a leaning tree. Also included are some additional data specific to lodgepole pine.

Timell notes that while trees with a high incidence of sweep, crook, lean, and fork contain more compression wood than straight stems, there apparently is no quantitative relationship between the amount and type of compression wood and the degree of stem displacement or

curvature. Most present-day investigators favor gravitational stimulus as the factor most probably involved in compression wood formation. Timell concludes that there is evidence of inheritance of a tendency to form compression wood per se, and that evidence for the inheritance of stem form and straightness, which are associated with the incidence of compression wood, is very strong.

Koch (1972, pp. 125-128) summarized, and illustrated with micrographs, essential features of compression wood in southern pines, which like lodgepole pine are hard pines—diploxylon members of the genus *Pinus*.

The literature contains a few papers specific to lodgepole pine—most of them stemming from work on plantations of the species introduced to England, Scotland, Ireland, and the Scandinavian countries. Comments on those most germane follow, along with some general comments on the anatomical and chemical characteristics of compression wood.

Physiology

Savidge (1983a, b) found that when vertical seedlings of lodgepole pine were brought in from the outdoors in late winter and placed in a darkened growth chamber, compression wood developed around the stem. In the same work, he reported that when indoleacetic acid was applied to a lodgepole pine shoot, compression wood developed immediately below the application site.

Timell (1986, p. 1247) concluded that the role of growth substances in the formation of compression wood is obscure though they do play some yet unexplained role in combination with gravistimulus; he further noted that it is highly uncertain, not to say improbable, that compression wood should be produced in mature trees as a consequence of redistribution of indoleacetic acid. A supra-optimal concentration of auxin, however, causes formation of compression wood. Among the auxins, idoleacetic acid, naphthalineacetic acid, and 2,4-dichlorophenoxyacetic acid are all known to induce compression wood formation when present in high enough concentrations.

See also the discussion of the mechanism of compression wood in righting a tree, under the heading "Stem Form and Compression Wood" in this section.

Anatomical Characteristics of Compression Wood

To understand the anatomical structure of compression wood in lodgepole pine, it is first useful to visualize the structure of normal wood in pines.

A wedge transversely cut from a lodgepole pine stem illustrates some of the features visible with the naked eye (fig. 3). The dark-colored **pith** is the small central core of parenchymatous tissue originating at the growing tip of the tree. On the periphery of the tree, wood is formed on one side and bark on the other side of the cambial layer. In a limb-free stem of lodgepole pine 76 to 228 mm in d.b.h., 85 to 91 percent of the volume is wood and 9 to 15 percent is bark—the proportion of bark being inverse to the d.b.h., so that small-diameter stems have a larger proportion of bark than large-diameter stems (Koch 1987, pp. 46 and 59).

Growth rings in lodgepole pine normal wood usually show an abrupt transition between the light-colored, thin-walled **earlywood** cells (fig. 4, 3-3a) formed early in the growing season, and the darker, thicker walled **latewood** (fig. 4, 4-4a) cells. (See figure 10 in the "Results" section for micrographs of transition from earlywood to latewood in normal and compression wood.) Total width of annual growth rings varies greatly in lodgepole pine, from barely visible with a hand lens to 4 or 5 mm (table 1). For all of the lodgepole pine trees in this study, growth ring width at 152-mm stump height averaged 1.00 mm for *latifolia* and 1.13 mm for *murrayana* (Koch 1987, pp. 20 and 53).

Heartwood (fig. 3) is darker than sapwood, contains no living cells, and because of resinous inclusions is less permeable and has less moisture content than sapwood. Heartwood volume in the lodgepole pine trees in this study, as a percentage of entire stemwood volume, was positively correlated with d.b.h., as follows (Koch 1987, pp. 273 and 299):

D.b.h.	***Latifolia***	***Murrayana***
mm	*Percent*	
76	22.0	10.3
152	28.3	16.9
228	34.2	20.3

The tissues and cell types observable by light microscopy in a block of southern pine wood are shown in figure 4; the cellular structure of lodgepole pine is very similar to that of southern pine (except that lodgepole pine lacks the longitudinal parenchyma, thick-walled parenchyma, spiral and callitroid-like thickenings, and pits on tangential walls of tracheids illustrated in figure 4). Pine wood consists principally of closely packed vertical cells, called **longitudinal tracheids**. Associated are horizontal tissues called **rays**, extending radially toward the pith, and specialized tissues surrounding vertical ducts called **resin canals**. Tracheids and other cells are interconnected through openings in the cell walls called **pits**, in most of which characteristic borders form **pit chambers**.

Cell walls are composed of elements too small to be visible through the light microscope, which is limited to about 0.2 micrometer (a micrometer is 10^{-3} mm). Electron microscopy, resolving to about 10 Angstrom (an Angstrom unit is 10^{-4} micrometers), reveals strands of **microfibrils**, some 100 to 300 Angstroms in diameter and of indefinite length, comprising the cellulose framework of the cell wall. These are in turn comprised of **elementary fibrils**, which presumably are cellulosic strands of the smallest possible cross-section—measuring about 35 Angstroms in diameter. An elementary fibril in turn consists of cellulose chains.

All of the horizontal elements in pine wood are contained in the rays (fig. 4)—ray tracheids, ray parenchyma, and epithelial cells.

Longitudinal elements of lodgepole pine wood are longitudinal tracheids, strand tracheids, and epithelial cells (fig. 4).

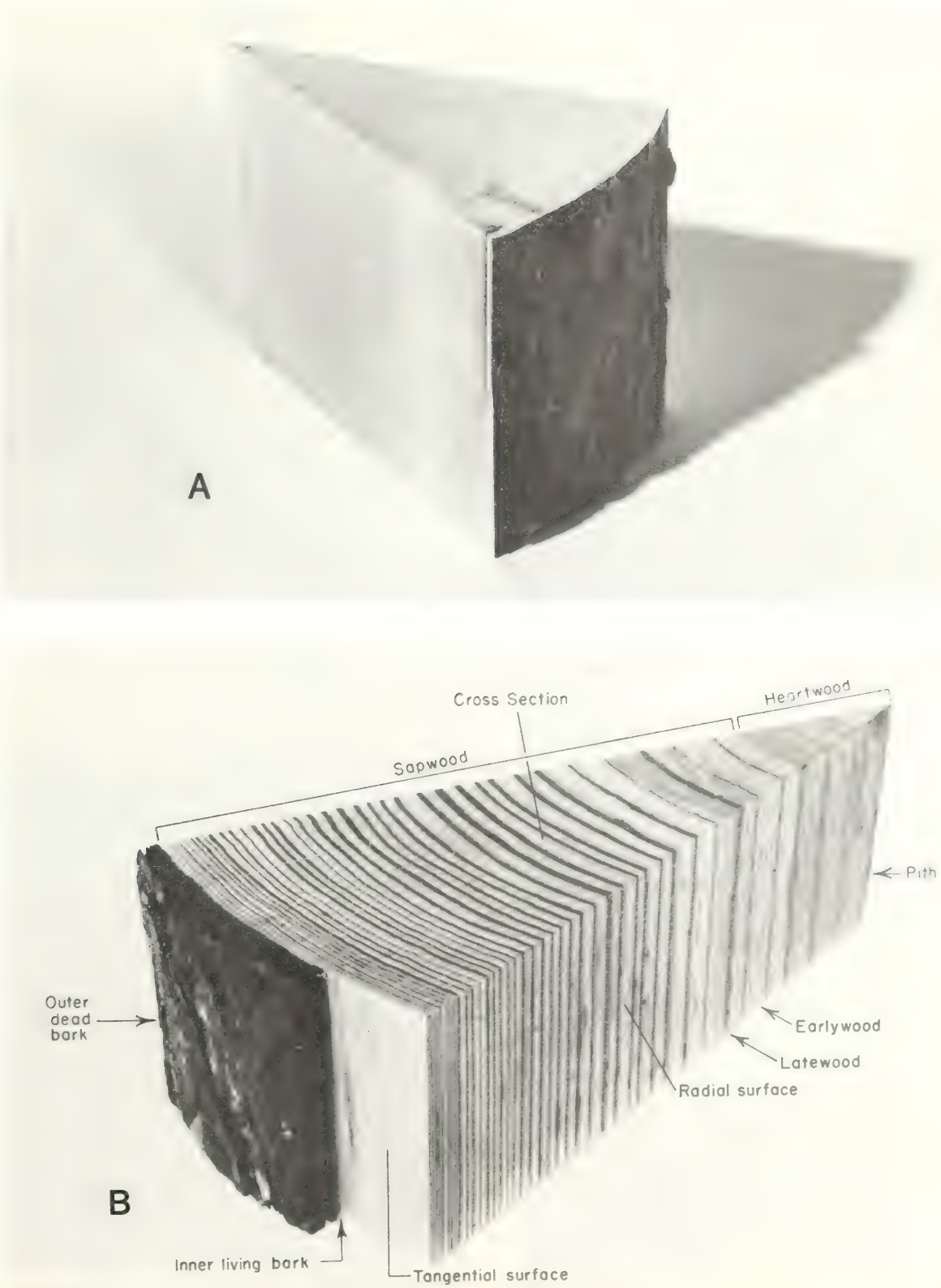


Figure 3—Gross anatomical features of stem sections from lodgepole and southern pines. (A) Typical narrow-ringed, thin-barked lodgepole pine with significant percentage of heartwood. The disk from which the wedge was cut measured about 90 mm in radius. (B) Typical fast-grown southern pine with thicker bark, wider rings, and more contrast between earlywood and latewood than lodgepole pine—and lesser percentage of heartwood in stems of comparable diameter.

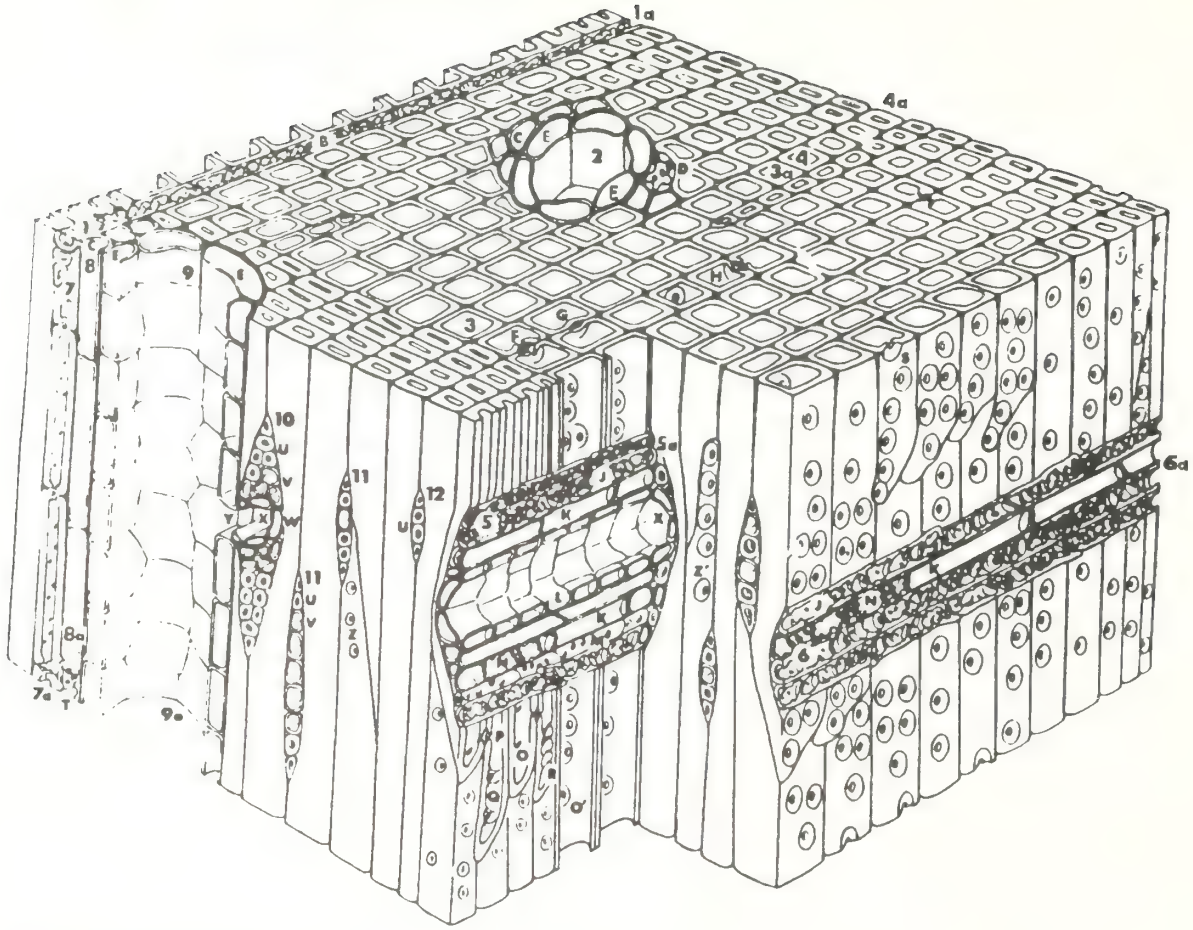


Figure 4—Typical southern pine wood. *Transverse view.* 1-1a, ray; B, dentate ray tracheid; 2, resin canal; C, thin-walled longitudinal parenchyma; D, thick-walled longitudinal parenchyma; E, epithelial cells; 3-3a, earlywood longitudinal tracheids; F, radial bordered pit pair cut through torus and pit apertures; G, pit pair cut below pit apertures; H, tangential pit pair; 4-4a, latewood longitudinal tracheids. *Radial view.* 5-5a, sectioned fusiform ray; J, dentate ray tracheid; K, thin-walled parenchyma; L, epithelial cells; M, unsectioned ray tracheid; N, thick-walled parenchyma; O, latewood radial pit (inner aperture); O', earlywood radial pit (inner aperture); P, tangential bordered pit; Q, callitroid-like thickenings; R, spiral thickening; S, radial bordered pits (the compound middle lamella has been stripped away, removing crassulae and tori); 6-6a, sectioned uniseriate heterogeneous ray. *Tangential view.* 7-7a, strand tracheids; 8-8a, longitudinal parenchyma, thin-walled; T, thick-walled parenchyma; 9-9a, longitudinal resin canal; 10, fusiform ray; U, ray tracheids; V, ray parenchyma; W, horizontal epithelial cells; X, horizontal resin canal; Y, opening between horizontal and vertical resin canals; 11, uniseriate heterogeneous rays; 12, uniseriate homogeneous ray; Z', small tangential pits in latewood; Z', large tangential pits in earlywood. (Drawing from Howard and Manwiller 1969.)

Because longitudinal tracheids make up more than 90 percent of the volume of pine wood, and because the differences between normal and compression wood in the structure of these cells account for the differences in their properties, further discussion is limited to longitudinal tracheids. For a fuller discussion of the anatomy of pine wood see Koch (1972).

Our intensive study of fiber length in lodgepole pine is incomplete, but existing literature indicates that longitudinal tracheids in mature lodgepole pine (var. *latifolia*) are $2^1/_4$ to $3^3/_4$ mm long, with average tangential diameter of about 27 microns. They are aligned radially as viewed in cross section (fig. 4) and have overlapping tapered ends.

The cell wall of the mature tracheid consists of an outer **primary wall** and a **secondary wall** (fig. 5a). Outside the primary wall is an **intercellular layer**, or **middle lamella**, composed largely of lignin. In the **secondary wall**, three layers are recognized; they are designated S_1 (outer), S_2 (middle), and S_3 (inner).

Tracheids of many of the hard pines, including the southern pines, have a warty layer lining tracheid lumens. Lodgepole pine tracheids appear to lack this feature; their interior walls are smooth (fig. 5b, left). Warty deposits were observed, however, within the bordered pit chambers of lodgepole pine (fig. 5b, right)—a feature typical of many species of the genus *Pinus*.

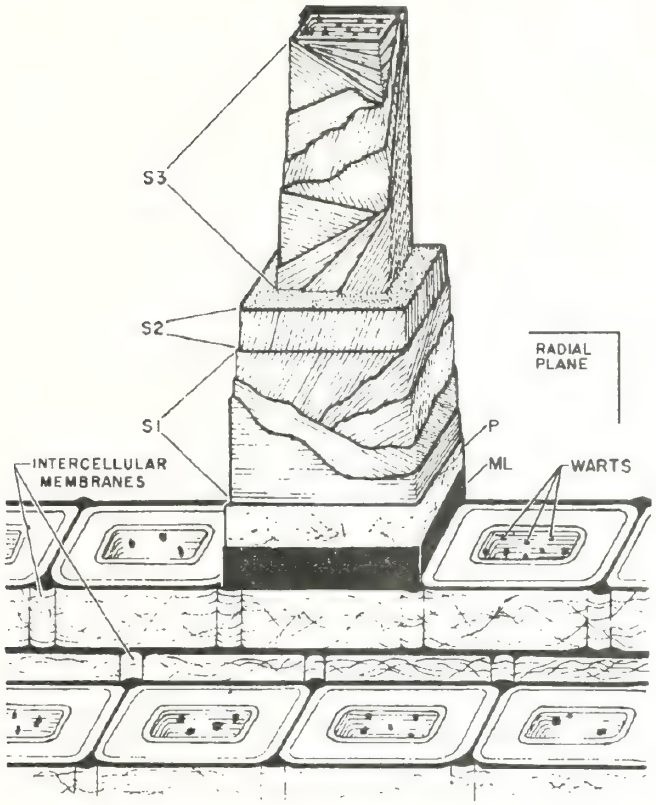
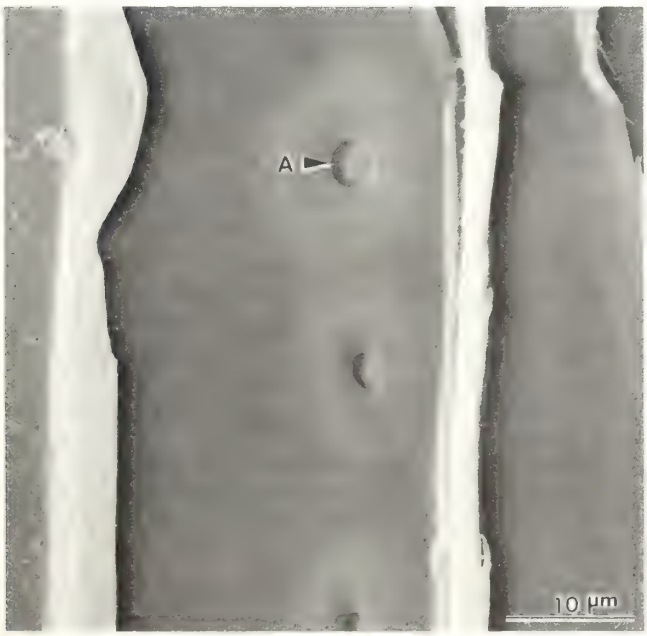
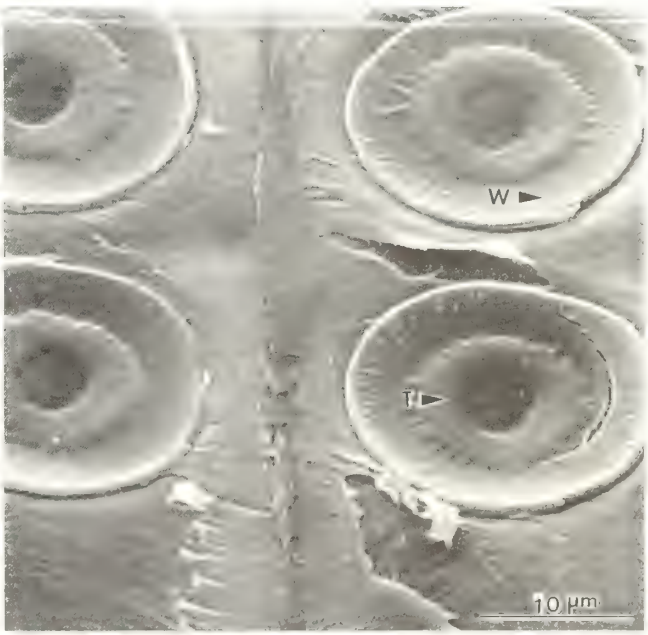


Figure 5a—Cell-wall structure of longleaf pine. A latewood longitudinal tracheid is exposed to show lamellae of the three layers of the secondary cell wall. Lines indicate alignment of microfibrils. ML is middle lamella. P is primary wall. S_1, S_2, and S_3 are layers of the secondary wall. (Drawing after Dunning 1969.) Lodgepole pine lacks the warty layer shown here (see fig. 5b). Also, lodgepole pine may have fewer lamellae in the S_1 and S_3 layers, and the S_2 may have several lamellae.



A



B

Figure 5b—Scanning electron micrograph of normal lodgepole pine wood. (A) Tracheid lumen walls with apertures of bordered pits; no warts visible. (B) Tracheid walls split longitudinally to expose, in radial aspect, portions of tracheids each with aspirated bordered pits and a coating of warts on pit chamber walls. W = warts; T = pit torus; A = pit aperture.

Three structural substances comprise the walls of wood cells. The framework is cellulose in the form of microfibrils. The matrix substances are hemicelluloses. Lignin occurs in intercellular layers and with the matrix materials surrounding the microfibrils; it may also be a component of the warty layers and the incrustation in cell interiors.

The outer envelope of longitudinal tracheids is the primary wall—a thin layer in which the cellulose microfibrils are randomly distributed. These fine strands are readily resolved with the electron microscope after some of the matrix substances have been removed (fig. 5a). Matrix polysaccharides, especially hemicelluloses, and pectin and lignin are the dominant components of primary walls.

In secondary cell walls, the framework of cellulose microfibrils is dominant. As previously noted, the secondary wall is comprised of three layers (fig. 5a): the outermost S_1, with multiple lamellae of microfibrils having varying alignments; the much thicker S_2 layer, which in normal wood has its microfibrils aligned most nearly with the longitudinal axis of the tracheid; and the thinner S_3 layer having multiple lamellae of varying alignments.

Fibril angle, the average angle between microfibrils in the S_2 layer and the tracheid longitudinal axis (fig. 6), is believed to be positively correlated with longitudinal shrinkage in wood.

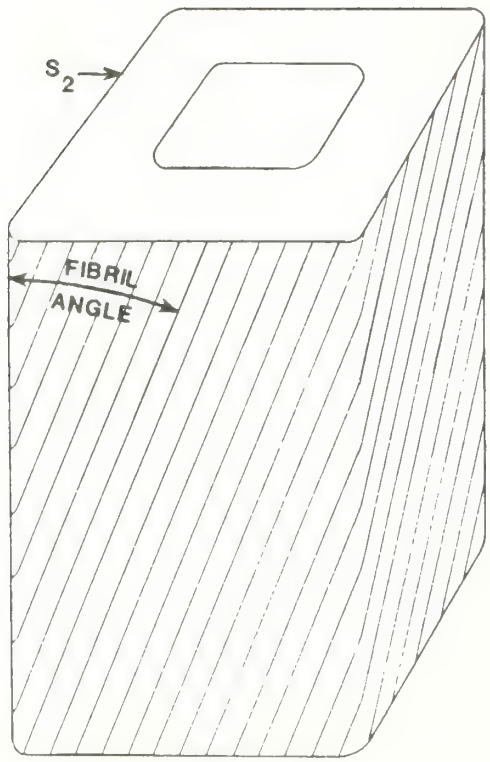


Figure 6—Fibril angle in the S_2 layer of the cell wall.

Longitudinal tracheids in compression wood differ from those of normal wood in a number of important ways that can be observed in transverse sections, as follows:

- Compression wood tissues show gradual transition from thin-walled earlywood cells to thick-walled latewood cells. (See figure 10 in "Results" section.)
- Tracheids in compression wood are distinguished by roundness of cells, by checks or cavities in the inner portion of the secondary wall, and by intercellular spaces. (See figure 11a in "Results" section.)
- With a polarizing microscope, it can be observed that the S_3 layer is missing from compression-wood tracheids. (See figure 11b in the "Results" section.)

Electron micrographs show that microfibrils in the S_2 layer of compression-wood tracheids make an abnormally large angle—sometimes more than 45°—with the longitudinal axis of the cell. This large angle, together with a higher lignin content than normal wood, impedes passage of light through cross sections of compression wood. In thin sections viewed over a light table, therefore, compression wood is readily discernible by its darker shades when compared to normal wood.

On a light table normal sapwood of lodgepole pine has a clear amber color; compression wood appears orange, to brown, to black depending on its severity. Depending on the presence of some or all of the attributes of compression wood discernible in cross section, that is:

- light impedence on a light table,
- gradual transition from thin-walled earlywood cells to thick-walled latewood cells (some authorities believe that the terms earlywood and latewood have little meaning when applied to compression wood),
- roundness of cells,
- presence of intercellular spaces,
- checks in the inner portion of the secondary wall,
- absence of S_3 layer,

the tissue under analysis can be classed as containing mild, moderate, or pronounced compression wood.

In this study, compression wood delineation was primarily accomplished by outlining areas with impeded light transmission. Scanning electron microscopy validations were periodically made on questionable areas. Researchers who have used this method of compression wood delineation will agree that such delineation can only be approximate.

Chemical Constituents of Compression Wood

A thorough review of the chemistry of compression wood is beyond the scope of this paper, but can be found in Timell (1986, pp. 289-468). Because of the significance of both cellulose content and lignin content to the pulp industry, however, it is useful to have some idea of the chemical constituents of both normal wood and compression wood of lodgepole pine.

Table 2—The average and range of pH and chemical composition of *latifolia* and *murrayana* trees with latitude, elevation, and tree diameter data pooled.[1,2] Data from Kim and others (1989)

Item	*Latifolia*		*Murrayana*	
	Average	Plus or minus	Average	Plus or minus
pH	4.57	(0.10)	4.64	(0.12)
Ash, percent	.26	(.05)	.28	(.06)
Extractives, percent	2.87	(.98)	2.41	(.67)
Lignin, percent	25.81	(.98)	26.40	(1.58)
Holocellulose, percent	80.40	(2.47)	83.26	(2.20)
Alpha cellulose, percent	49.64	(2.54)	51.83	(2.54)

[1]Each value is a mean from the 243 *latifolia* or 36 *murrayana* trees.
[2]The moisture (ASTM D 2016-74), ash (ASTM D 1102-56), ethanol-toluene extractives (ASTM D 1107-56), lignin (ASTM D 1106-56), and alpha cellulose (ASTM D 1103-60) content were measured following standard procedures. Toluene was substituted for benzine in the extractive analysis (Goetzler 1982). The pH and chlorite holocellulose contents were measured using the Forest Products Laboratory Methods 67-033 and 67-018, respectively. The average chemical composition was calculated on an ovendry wood basis.

Stemwood-average analyses of var. *latifolia* and var. *murrayana* performed on the same 279 lodgepole pine trees that were used in the current study of compression wood yielded mean values of near 50 percent for alpha cellulose and about 26 percent for lignin (table 2). The specimens for these analyses were taken at tenth points in height up each tree, in a manner similar to that used in sampling for the compression wood study here reported. Because any compression wood present in the stem was included in the chemical-analysis samples, the overall analyses probably indicate a lower cellulose content and a higher lignin content than if the specimens had been rigorously screened to exclude all compression wood.

Although no published data are available defining the chemical constituents of compression wood in lodgepole pine stemwood, a wealth of data are available for other conifers, including a number of hard pines. Based on all the published data Timell (1986, pp. 391 and 458) concludes, in part, that:

> In general, the difference in chemical composition between normal and compression woods of the majority of conifers is of a quantitative rather than qualitative nature. . . . Compression wood contains 30-40% more lignin and 20-25% less cellulose than normal wood.
>
> The middle lamella and primary wall (in compression wood) evidently have the same composition as normal wood, with a relatively low cellulose and high pectin content. . . . The distribution of lignin in the tracheids of compression wood is highly characteristic and sets the tissue apart from normal wood. The unusually high lignin and low polysaccharide contents of the S_2 layer are unique among wood cells.

Prevalence of Compression Wood and Effect on Mechanical Properties

Only one publication specific to lodgepole pine was found to compare mechanical properties of normal wood to that containing compression wood. Koch and Barger (1988) sampled a pair of lodgepole pines 3.5 to 4 inches in diameter from each of 28 public forests in six northwestern States of the United States, and took specimens of stemwood from 20 percent of tree height. Of the 56 trees, 14 (25 percent) had compression wood—usually accompanied by more than average pith eccentricity, as follows:

State and forest	Degree of compression wood	Pith eccentricity
		Inch
Colorado		
Gunnison, tree #1	mild	0.1
Gunnison, tree #2	mild	.1
Bureau of Land Management, tree #2	mild	.4
Idaho		
Challis, tree #1	mild	.2
Challis, tree #2	mild	.1
Panhandle, tree #1	moderate	.2
Panhandle, tree #2	moderate	.3
Oregon		
Fremont, tree #1	mild	.1
Fremont, tree #2	moderate	.1
Mount Hood, tree #1	pronounced	.3
Mount Hood, tree #2	pronounced	.5
Washington		
Wenatchee, tree #2	mild	.4
Wyoming		
Bridger-Teton, tree #2	mild	.3
Shoshone, tree #2	mild	.2

The 9-inch-long stem sections evaluated—each containing a knot cluster—were air-dried, lathe-turned to $2^1/_4$ inches in diameter, and tested to destruction in compression parallel to the grain. Specimens containing compression wood (14 in number) had significantly lower properties—adjusted to a wood moisture content of 10 percent of ovendry weight—than those without compression wood (42 in number), as follows:

Property	No visible compression wood	Visible compression wood
	Psi	
Modulus of elasticity	1,270,000	940,000
Maximum crushing strength	5,920	5,250
Proportional limit	4,130	3,030

Knots and Compression Wood

Because compression wood is associated with knotwood, albeit in ways not entirely clear, the percentage of knotwood in stemwood is of interest. No data are available for North American stands of lodgepole pine, but Hakkila and Panhelainen (1970) sampled lodgepole pine (var. *latifolia*) stands in Finland established from seed mainly obtained between latitudes 50 and 51 degrees in Alberta and British Columbia. The trees had mean age of 40 years, mean d.b.h. of 5.0 inches, mean height of 44 feet, and crown ratio of 52 percent. They found that the percentage of knotwood in stems from South Finland (0.98 percent) was significantly less than the percentage in North Finland (1.67 percent), and that the percentage of knotwood increases from about 0.4 percent near the butt to about 2.4 percent in the upper portion of the stem (fig. 7).

Timell's (1986, pp. 804-808, 926-930) survey of the literature suggests that branches of practically all conifer's branches have at least some compression wood, and most of them contain sizable amounts. Stemwood knots, because they are basal parts of branches, always contain some compression wood, and often have large amounts. Associated with the knotwood are significant amounts of stemwood compression wood—particularly in the stem immediately below the knot, as will be further discussed in the "Results" section of this report.

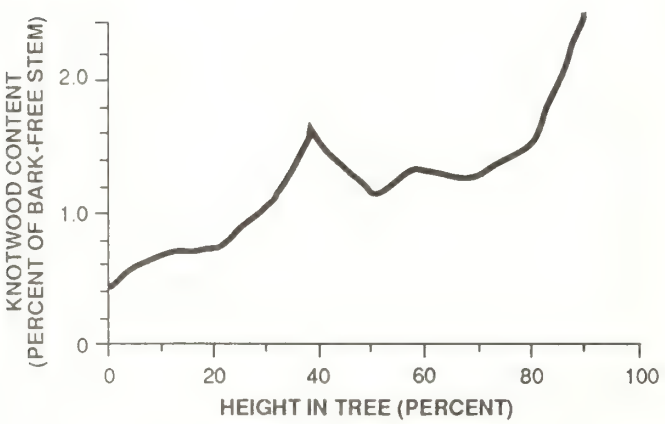


Figure 7—Longitudinal variation of knotwood percentage with height in stem of lodgepole pine (var. *latifolia*) grown in Finland from Canadian seed sources. (Drawing from Hakkila and Panhelainen 1970.)

Stem Form and Compression Wood

Sweep is common in conifers in general and is much evident in European plantations of lodgepole pine—particularly those of coastal origin. The literature—see Timell (1986 pp. 714-716, 758-773, 1270-1295)—indicates that crook is more strongly heritable than sweep and lean, which are often caused by environmental factors such as wind or snow.

Trees with a high incidence of sweep, crook, lean, and fork have more compression wood than straight trees—although the quantitative correlation between compression wood content and degree of these features is not outstanding. Scientists concerned with relating stem form to compression wood in lodgepole pines should find useful the following references:

Citation	Conclusion
Lines (1980)	Lodgepole pines in Europe, when exposed to wind, will develop a persistent lean rather than a broad sweep; such trees will have much compression wood.
Brazier (1966, 1980)	Compression wood is very common in British-grown lodgepole pine and most frequently occurs on the northern and eastern sides of the stem, away from the prevailing winds.
O'Driscoll (1980)	Results in Ireland similar to those reported by Brazier.

Timell's (1986, pp. 1745-1797) review of the literature related to the mechanism of compression wood action in righting a tree leads to his conclusion—in part—as follows:

> In vertically growing mature trees, the periphery and outer layers of the stem are in tension while the center is in compression. Leaning conifers, by contrast, are subjected to considerable compressive stress along both the lower and upper periphery, while the central portion is in tension. The compression on the lower side is partly due to the weight of the tree but largely to the active pressure exerted by the longitudinally expanding compression wood. The latter pressure is also responsible for the compressive stress on the upper side of the stem, a stress that is somewhat mitigated by the opposite, tensile stress caused by the weight of the tree.
>
> The mechanism by which compression wood is brought to expand along the grain in the living tree has not yet been fully clarified. The elongation could be caused by an increase in length over that of the fusiform initials in conjunction with an absence of gliding growth. It is more likely, however, that the elongation is associated with the deposition of lignin in the tracheid wall. Lignification probably results in a swelling of the cell wall, and when the microfibril

angle exceeds 30-40°, this swelling causes a longitudinal compressive stress. It has been estimated that this stress is five time larger than the tensile stress developed by normal wood and far in excess of any force that could arise in the active cambium. Regardless of the actual cause of the axial pressure exerted by compression wood, its origin must be sought in the differentiating tracheids.

European literature on lodgepole pine stem form is more extensive than that of North America, and originates principally from study of plantations in England, Scotland, Ireland, Sweden, and Finland. Some conclusions are referenced in the following paragraphs.

In British plantations of lodgepole pine, lean and basal sweep are common, particularly in stands originating from the coastal areas of Washington and Oregon (Davies 1980; Henderson and Petty 1972; Lines 1980; Lines and Booth 1972; Moss 1971; Remrod 1973).

In Ireland, the coastal variety of lodgepole pine has been favored over the inland type because of its more rapid growth, and in spite of its greater tendency toward basal sweep and stem sinuosity (Carey and Griffin 1981; Fitzsimons 1982; Lines 1957; Lynch 1980; Mooney 1966; O'Driscoll 1980; Pfeifer 1982).

In Sweden, variety *latifolia* is preferred over the coastal variety because of its rapid height and radial growth, but southern provenances are susceptible to stem malformation from wind and snow, and lodgepole pines planted in southern Sweden have shown a high incidence of bend, crook, forks, sinuosity, and coarse branches (Blomquist 1981; Fryk 1980, 1981; Hagner 1971, 1983; Karlman 1981; Lindgren 1980).

In southern Finland, lodgepole pine in 50-year-old stands yielded about the same volume of sawlogs as did *Pinus sylvestris*, in spite of lodgepole having more forked and multistemmed boles, and somewhat more crooked stems, than Scots pine (Lahde and others 1982).

Radial and Height Distribution of Compression Wood In Stems

The literature on compression wood distribution in coniferous stems is voluminous (see Timell 1986, pp. 773-822), but none of the published studies contain information specific to lodgepole pine. The reader is therefore referred to the "Results" section of this report.

Effect of Compression Wood on Warp in Lumber

Literature is abundant on longitudinal shrinkage of compression wood, but none of the published data are specific to lodgepole pine. Data on other hard pines, however, suggest that compression wood shrinks about tenfold (fourfold to fortyfold) more than normal wood of the hard pines (Timell 1986, p. 516). This disparity in longitudinal shrinkage between compression wood and normal wood can cause severe drying distortion in lumber.

Stemwood-average analysis of varieties *latifolia* and *murrayana* sampled from the same 279 lodgepole pine trees that were used in this study of compression wood yielded mean values of longitudinal shrinkage—green to ovendry—as follows (Wiedenbeck and others, in press):

Variety	Radial position in tree	
	Corewood	Mature wood
	- - - - - - - *Percent* - - - - - - -	
Latifolia	0.472	0.145
Murrayana	1.109	.243

Specimens for the foregoing analysis were not selected to totally exclude compression wood, so they more-or-less represented the natural mix of normal and compression wood. The shrinkage values suggest that the *murrayana* stems had more compression wood than the *latifolia* stems; this is consonant with findings reported in the "Results" section.

Two references were found relating warp in sawn lodgepole pine to compression wood content.

Malcolm's (1968) data do not expressly include correlation between compression wood content and lumber warp, but he implies such a relationship. In his study, 8-foot butt sections from small lodgepole pine sawlogs (variety and geographic area not specified, but probably var. *latifolia* from the Rocky Mountain region of the United States) were sawed into 2 by 4 studs and kiln dried to evaluate warp as related to stump height and degree of crook in the butt section of each bole. Malcolm found that studs cut from crooked butt sections warped more than those from straight butt sections—probably mainly attributable to greater compression wood content in the crooked butts. In trees with crooked butt sections, stud warp was minimized if the stud log was taken starting 3 or 4 feet above normal stump height. Malcolm concluded, therefore, that to minimize stud warp the first 3 or 4 feet of the butt ends of lodgepole pines with crooked lower boles should be chipped for pulp rather than sawn for lumber.

Posssibly stimulated by Malcolm's (1968) findings, Hallock (1969) studied warp in 2 by 4 studs cut from 8-foot lodgepole pine logs 6 to 12 inches in diameter obtained from the vicinity of West Yellowstone, MT. The logs, limited in sweep to 1 inch or less in the length of the log, were inspected on the sawn ends and classified as containing compression wood or not containing compression wood. Hallock found that no difference in yields of grade 1 studs or in their average warp could be attributed to the presence or absence of visually evident compression wood. He commented that: "because the warping effect of compression wood especially if located along one edge or face of a stud can hardly be denied, the only rational conclusion is that compression wood is not easily identifiable visually on the log ends in lodgepole. Thus it is possible that a substantial part of the sample classified *compression-wood absent* actually contained compression wood."

The authors of this paper, after light-table analysis of 2,790 lodgepole pine stem sections, concur with Hallock that compression wood is not easily identifiable on the ends of lodgepole pine logs in a woods or mill environment.

GENERAL STUDY PROCEDURE

Locating and Selecting the 243 *Latifolia* Trees

The sample area spanned from 40 to 60 degrees (inclusive) at 2.5-degree intervals; the width of the sample area was 10 degrees of longitude, with sample area shifting 2.5 degrees west for each 2.5 degrees shift north in latitude (fig. 1). Sample band width was 0.5 degree of latitude on each side of the nominal latitude line; each latitude band was 1 degree deep in the north-south direction (60 nautical miles), and 10 degrees of longitude wide in the east-west direction.

Within each of these nine latitudinal sampling bands, natural unthinned stands were identified with the following constraints: adjacent to road traversable by pickup truck; within boundaries of National or Provincial forests; and containing some more-or-less level benches or flats.

It was found that at least nine such stands could be identified within each sampling band. The identified stands were ranked by elevation, and then the three highest, the three most intermediate, and the three lowest were selected for sampling. These elevational zones were highest in the south and lowest in the north; elevational zone width was broadest at midlatitude (fig. 2).

On a bench or flat typical of each of these selected stands, single trees 76 mm, 152 mm, and 228 mm in d.b.h. and free of insects and diseases were taken that in the collector's view typified within-stand trees of these diameters on that bench or flat. Thus 27 *latifolia* trees were taken from each of the nine latitudes—3 diameters x 3 elevations x 3 replications, for a total of 243 trees.

It is important to note that this sampling scheme resulted in selection of 76-, 152-, and 228-mm trees that were of approximately the same age, because most of the stands were of fire origin. Thus, most of the small-diameter trees were suppressed, while the larger trees were the fast growers (table 1).

Locating and Selecting the 36 *Murrayana* Trees

The sample areas extended from 37½ to 45 degrees latitude at 2.5 degree intervals; trees were sampled at 37½, 40, 42½, and 45 degrees—but only at one longitude per latitude (fig. 1).

The same three constraints on location applied to *latifolia* also applied to *murrayana*, but *murrayana* was sampled only from midelevation as follows:

Latitude	Elevation	
Degrees	*Meters*	*Feet*
37½	2,402	7,880
40	1,676	5,499
42½	2,006	6,581
45	1,148	3,766

Thus nine *murrayana* trees were taken from each of the four latitudes—3 diameters x 1 elevation x 3 replications, for a total of 36 trees.

Field and Laboratory Work

For a complete description of the field work see Koch (1987, p. 9). See table 1 for summary information on the trees collected.

Stem Procedure—In the field the stem was shorn of branches so that it was complete from 152-mm-high stump to apical tip. By stretching a taut string between the 10- and 70-percent stem levels, the maximum crook was measured and recorded together with the stem level at which it occurred.

From the 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, and apical-tip level of the stem a pair of disks were removed—one 50 mm thick and bagged in polyethelene for laboratory determination of moisture content and specific gravity, the other 75 mm thick and air-dried for laboratory determination of additional properties.

Also transported from field to laboratory were two stem sections with bark in place—the first between stem levels 10 and 20 percent, and the second between 20 and 30 percent. In the laboratory these two stem sections were debarked and both wood and bark air dried and stored.

In the laboratory the number of annual rings at stump height was recorded, and the characterization disks air dried and stored. Each moisture disk was weighed green, its volume measured by water immersion, and its bark thickness (as measured by diameter tape before and after debarking) recorded. The debarked disk was weighed and its volume recorded. Heartwood was indicated by application of ferric chloride solution (10 g FeCl in 90 g water) and split away from the sapwood, heartwood diameter was measured, and heartwood weight and volume recorded. The ovendry weights of bark, sapwood, and heartwood of each disk were then recorded.

Determining Compression-Wood Content—From each of the 2,790 characterization air-dried disks of stemwood (10 disks from each of the 243 *latifolia* trees and 10 disks from each of the 36 *murrayana* trees) a slice 3 mm thick was accurately cut with a smooth-trim saw. Each disk was placed on a light table to reveal its compression wood content using the method of Pillow (1941). The disk outline and the outline of the compression wood present were delineated on a transparent sheet of appropriate size. A dot grid was then superimposed on the transparency, and a count made of the dots within the entire disk and within the areas of delineated compression wood. From these counts, six columns of data were derived:

1. Number of the dots within each entire stemwood disk.
2. Number of dots within the areas of compression wood delineated on each disk.
3. The percentage of each disk area represented by compression wood.
4. The total number of dots within the entire 10 disks of each tree.
5. The number of dots within the compression wood content of all 10 disks of each tree.
6. The percentage of the entire stemwood of each tree represented by compression wood.

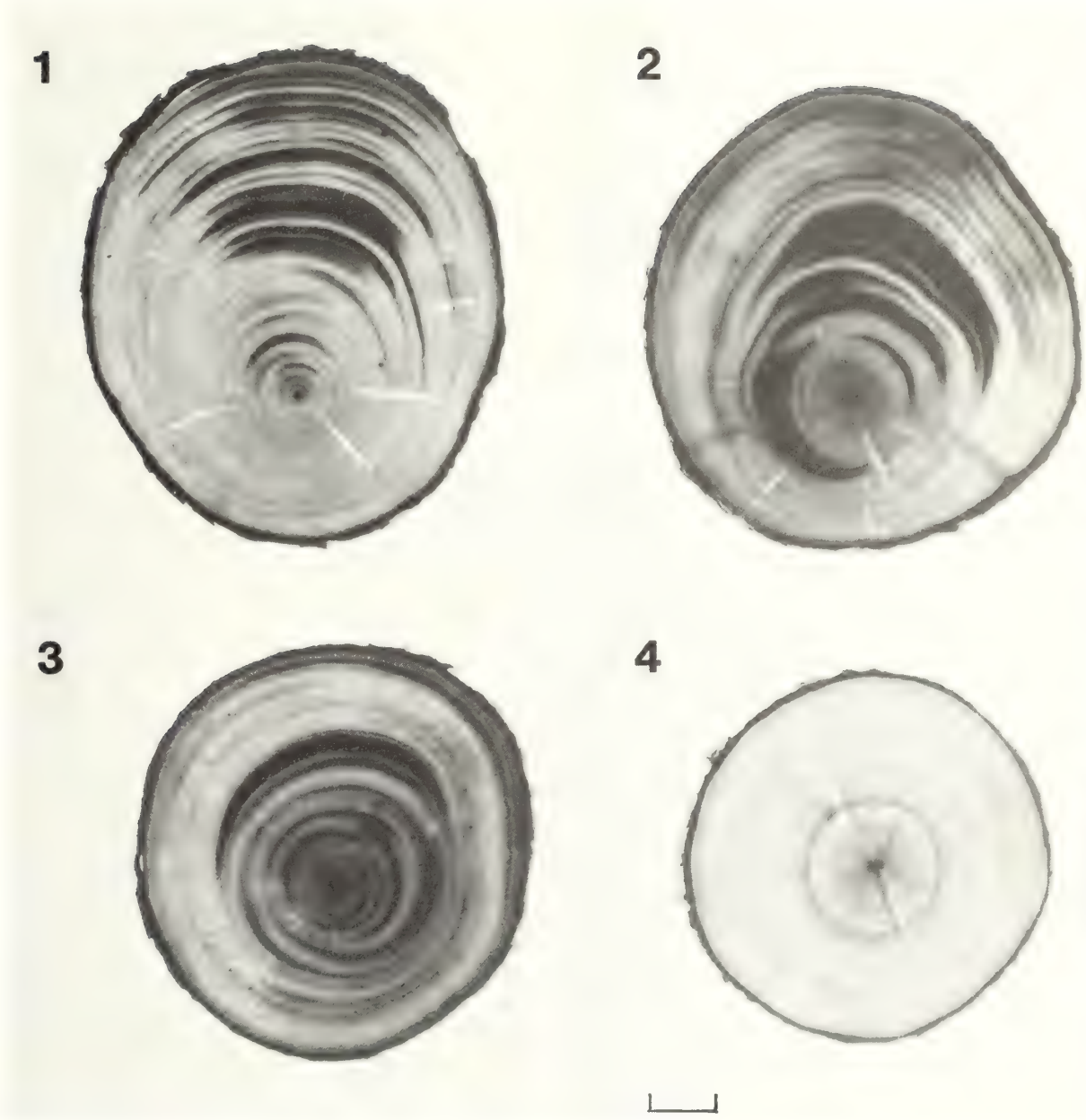


Figure 8—Compression wood patterns (dark areas) in lodgepole pine as viewed by transmitted light: (1) usual development in eccentric stem; (2) large areas of compression wood on opposite sides of pith; (3) circling concentric streaks of compression wood from pith to bark; (4) disk with almost no compression wood. The scale mark shows 1 cm.

The data from items 3 and 6 were entered on master computer-input data sheets, item 3 showing trends by height in each tree, and item 6 being a tree-average value.

Additionally, a code number was entered to designate the pattern in which the compression wood appeared using a classification similar to that of Boone and Chudnoff (1972); see figure 8:

1 = usual eccentric
2 = opposite
3 = concentric
4 = almost none or none

Also, a number was entered designating the absence or presence of knots:

0 = no knots
1 = knot or knots present in section

From these data, for each tree an arithmetic mean of the volume percentage of compression wood in sections with knots was derived and compared to the volume percentage of compression wood in those sections without knots.

Because the disks were taken to avoid obvious knot clusters (inclusion of which would have confounded clearwood specific gravity determinations), total compression

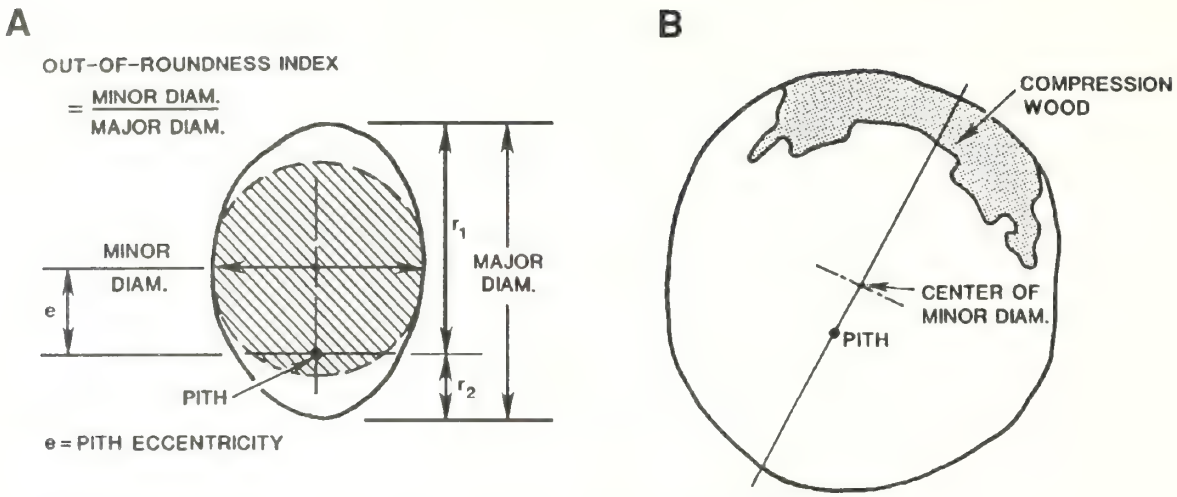


Figure 9—(A) Definition of section maximum diameter (maximum caliper inside bark, air dry), minor diameter (the diameter of the largest circle that could be inscribed within the section), r_1, r_2, out-of-roundness index, and pith eccentricity (e). (B) Section illustrating the typical case in which a line projected through pith and minor-diameter center intersects the compression-wood area on the r_1 side only.

wood associated with immediate proximity to knot clusters in the stemwood was not evaluated.

If, as reported by Hakkila and Panhelainen (1970), knotwood comprises about 1⅓ percent of lodgepole stemwood, and if associated compression wood is twice the knotwood volume, then compression wood related to knotwood might be about 2⅔ percent of stemwood volume; this computation is based on speculation, however. The study was not designed to ascertain the percentage of stemwood volume represented by knot-associated compression wood, however, since obvious knot clusters were avoided if practical when sample sections were taken.

Determining Pith Eccentricity—Pith eccentricity of each disk (fig. 9) was determined by overlaying each bark-free disk with a transparency containing concentric circles inked at 2-mm intervals of radius. The rings were placed to be as nearly as possible coincident with the stemwood section to include the largest ring possible, and the eccentricity of the pith (from the center point of this largest included ring) measured to the nearest millimeter. An arithmetic average of eccentricities of the 10 disks (levels 0, 1/10, 2/10, 3/10, 4/10, 5/10, 6/10, 7/10, 8/10, and 9/10) provided a statistic representative of the tree average.

At the same time the major (major caliper) and minor (largest circle contained within the section) diameters of each disk were recorded (fig. 9) and the minor diameter expressed as a proportion of the major diameter—which provided a measure of the out-of-roundness of each section. An unweighted arithmetic mean of these ten statistics for each tree provided a tree-average index of stemwood out-of-roundness.

Recorded on the master computer-data input sheets, was the following information on the air-dried disks:

1. Pith eccentricity of each disk, millimeters
2. Tree-average pith eccentricity, millimeters
3. Index of out-of-roundness of each disk (minor diameter/major diameter)
4. Tree-average index of stemwood out-of-roundness

Additionally, on the transparency tracing of each section, a line was drawn from the pith through the center-point of the minor-diameter circle (fig. 9) and values for r_1 and r_2 recorded. From these values the ratios r_1/r_2, and e/r_1 were computed. When extended across the section, this line usually passed through compression wood areas within the section—but not always. Therefore the following code was used to record the situation:

0 = line missed all compression wood area
1 = line passed through compression wood areas on r_1 side
2 = line passed through compression wood areas on r_2 side
3 = line passed through compression wood areas on both r_1 and r_2 sides
4 = no compression wood in section.

Statistical Analysis

Analysis of variance was made in three groupings (table 3): *latifolia* throughout its principal latitudinal range of 40 through 60 degrees; *murrayana* through its primary latitudinal range of 37½ through 45 degrees; and *latifolia* compared to *murrayana* at the three common latitudes of 40, 42½ and 45 degrees (medium elevation only).

For each of the two varieties, standard deviations for measured tree characteristics were noted—usually by diameter class, with all other factors pooled.

Correlations of interest observed in *latifolia* between tree characteristics (including those described in Koch [1987]) were also determined.

Table 3—Analysis of variance format

Source	Degrees of freedom
Latifolia	
Latitude (L)	8
Elevation (E)	2
Diameter (D)	2
L x E	16
L x D	16
E x D	4
L x E x D	32
Error	162
Total	242
Murrayana	
Latitude	3
Diameter	2
L x D	6
Error	24
Total	35
Latifolia* compared to *Murrayana	
Variety (V)	1
Latitude	2
Diameter	2
V x L	2
V x D	2
L x D	4
V x L x D	4
Error	36
Total	53

RESULTS—GENERAL OBSERVATIONS ON ANATOMY

Cellular Structure and Wood Color

The transition from earlywood to latewood is gradual in compression wood (fig. 10), whereas it is usually abrupt in normal wood. As noted previously, pronounced compression wood in transverse section (fig. 11a) is characterized by roundness of cells, presence of intercellular spaces, checks in the inner portion of the secondary wall, and (fig. 11b) absence of the S_3 layer. Mild or moderate compression wood may display only two or three of these four attributes.

The color of normal lodgepole pine sapwood viewed in thin sections over a light table is light amber. Compression wood is discernible as more-or-less opaque areas—ranging in color from orange smudges (mild), to brown areas (moderate), to nearly black masses (pronounced). Micrographs of areas containing these colorations confirmed these degrees of compression wood severity.

Patterns of Compression Wood

Patterns of compression wood can be classified as shown in figure 8, with most sections developing compression wood on the r_1 side (fig. 9 right and table 4), and most showing primarily annular patterns developed over less than 180° segments. When compression wood is mild, it is usually concentrated in the latewood of annual rings.

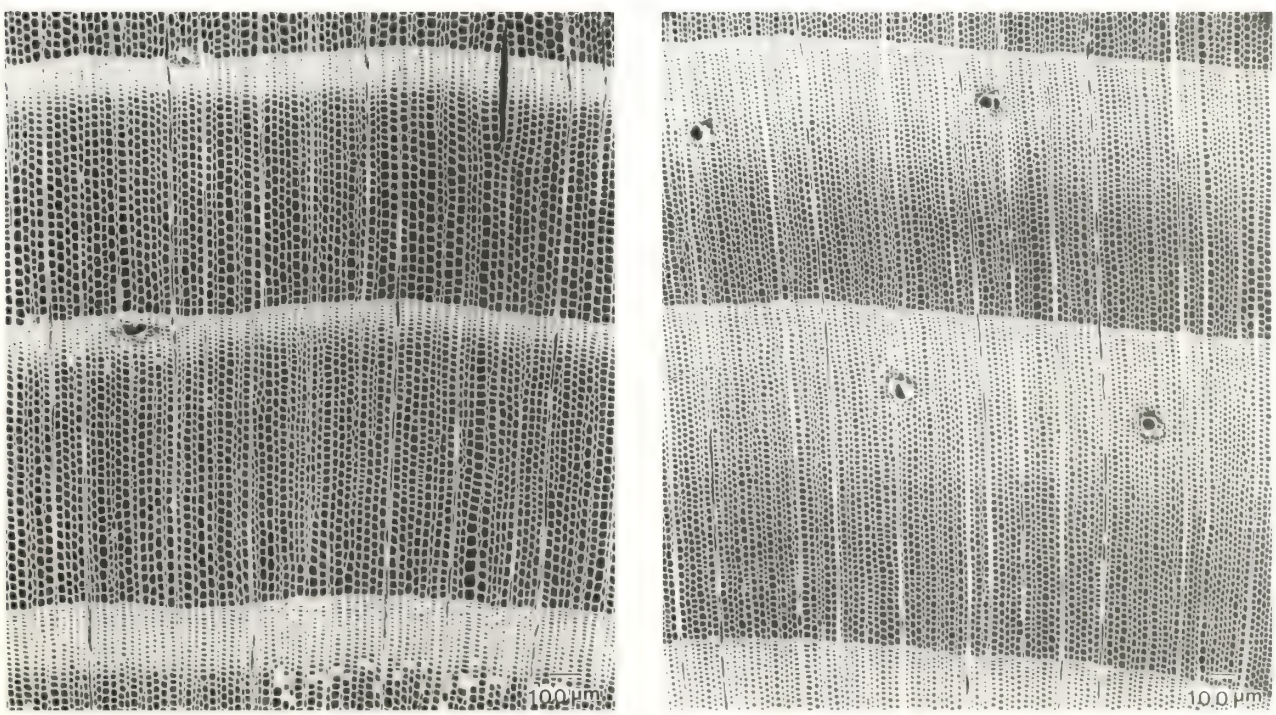
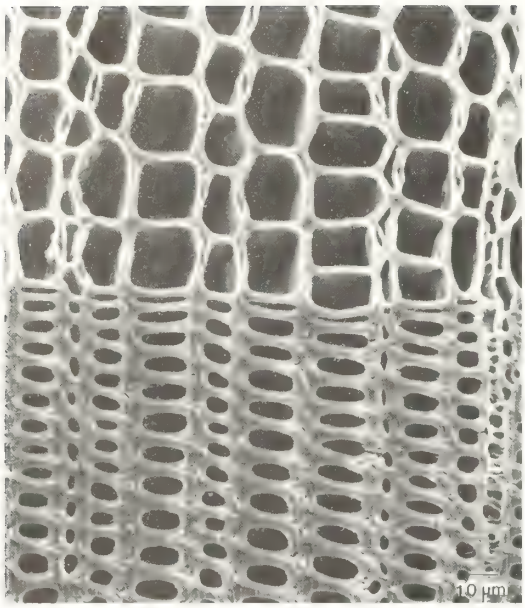
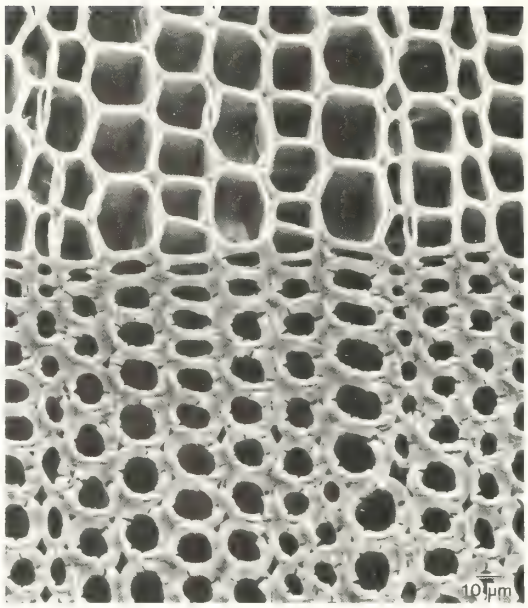


Figure 10—Photomicrographs of cross sections of normal lodgepole pine wood (A) and compression wood (B). In normal wood the transition in cell size and wall thickness is abrupt between earlywood and latewood; compression wood exhibits a gradual transition in these dimensions.

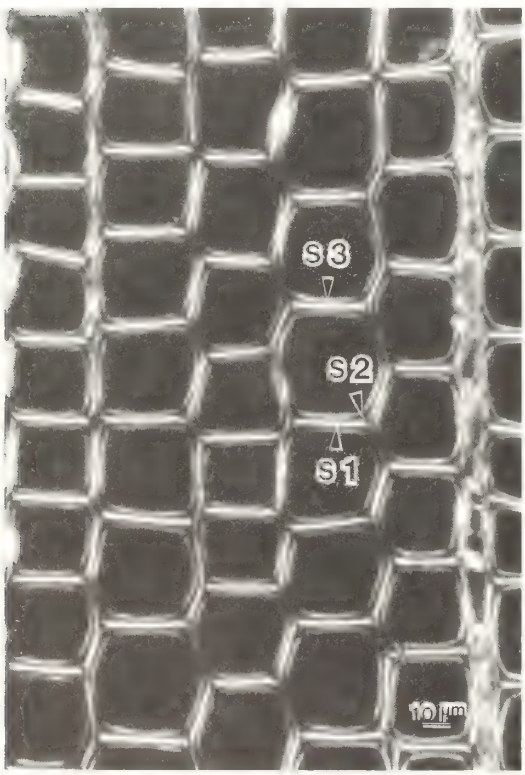


A

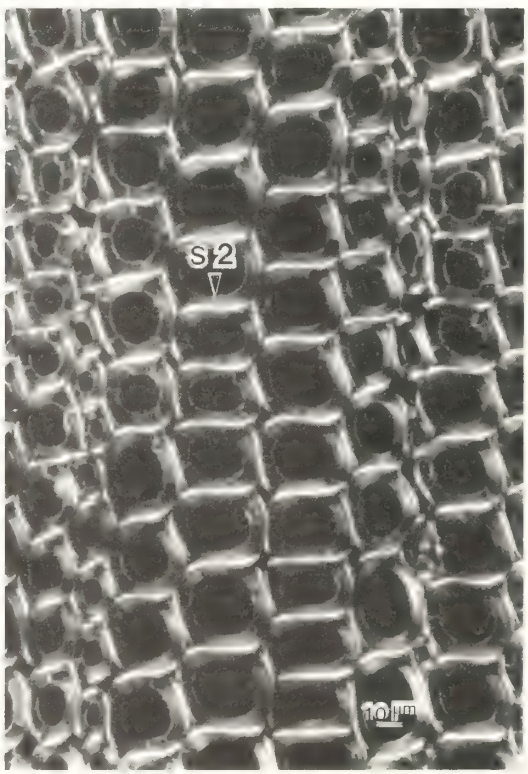


B

Figure 11a—Scanning electron micrographs of lodgepole pine normal wood (A) and compression wood (B). The earlywood tracheids at the top of each micrograph are similar in size and shape. The latewood tracheids show significant differences, however. Rounded tracheids, intercellular spaces, and "checked" walls are typical of compression wood—in marked contrast to normal latewood cells.



A



B

Figure 11b—Polarized-light micrographs of lodgepole pine. (A) Normal wood displaying typical three-layered cell walls (bright S_3, dark S_2, and bright S_1). (B) Compression wood with S_3 layer absent.

As noted above it most frequently occurs (47 percent of all sections examined) in pattern #1, with intermittent years, or groups of years, affected (fig. 12). From such frequent patterns, one might infer that each lodgepole pine has a sensing and correction system that functions to maintain its stem in an erect mode. One could visualize this system operating much like the automatic pilot system of an airplane that maintains it in level flight. An observer of the controls of an airplane operating under the automatic pilot sees the controls periodically move to restore attitude; much of the time, however, the controls are in neutral. Thus it seems that the tree periodically signals for formation of compression wood to right itself, and then switches off the signal when the correction is complete.

Not infrequently trees overcorrect, possibly giving rise to pattern #2 (fig. 8).

Patterns in *Latifolia* Compared to Those in *Murrayana*.—The most prevalent compression wood pattern in sections of both *latifolia* and *murrayana* was pattern #1 (fig. 8), which occurred in 47 percent of all sections examined in each variety. About one-third of the total sections in each variety had little or no compression wood, as follows:

Pattern (see fig. 8)	2,430 sections *latifolia*	360 sections *murrayana*
	Percent	
#1	47.0	47.2
#2	9.1	2.5
#3	9.3	6.7
#4	34.6	33.6
Total	100.0	100.0

Pattern Variation With Tree D.b.h.—*Latifolia* and *murrayana* trees 76 mm in d.b.h. have a smaller percentage of sections with little or no compression wood (and—in *latifolia*—a larger percentage with compression wood pattern #1) than trees 152 mm and 228 mm in d.b.h. (table 4).

Pattern Variation With Elevational Zone—Distribution of patterns of compression wood in *latifolia* appears to be unrelated to elevational zone, as follows:

Pattern in *latifolia*	Elevational zone		
	Low	Medium	High
	Percent		
#1	47.5	46.3	47.1
#2	9.6	8.4	9.4
#3	7.0	10.5	10.4
#4	35.9	34.8	33.1
Total	100.0	100.0	100.0

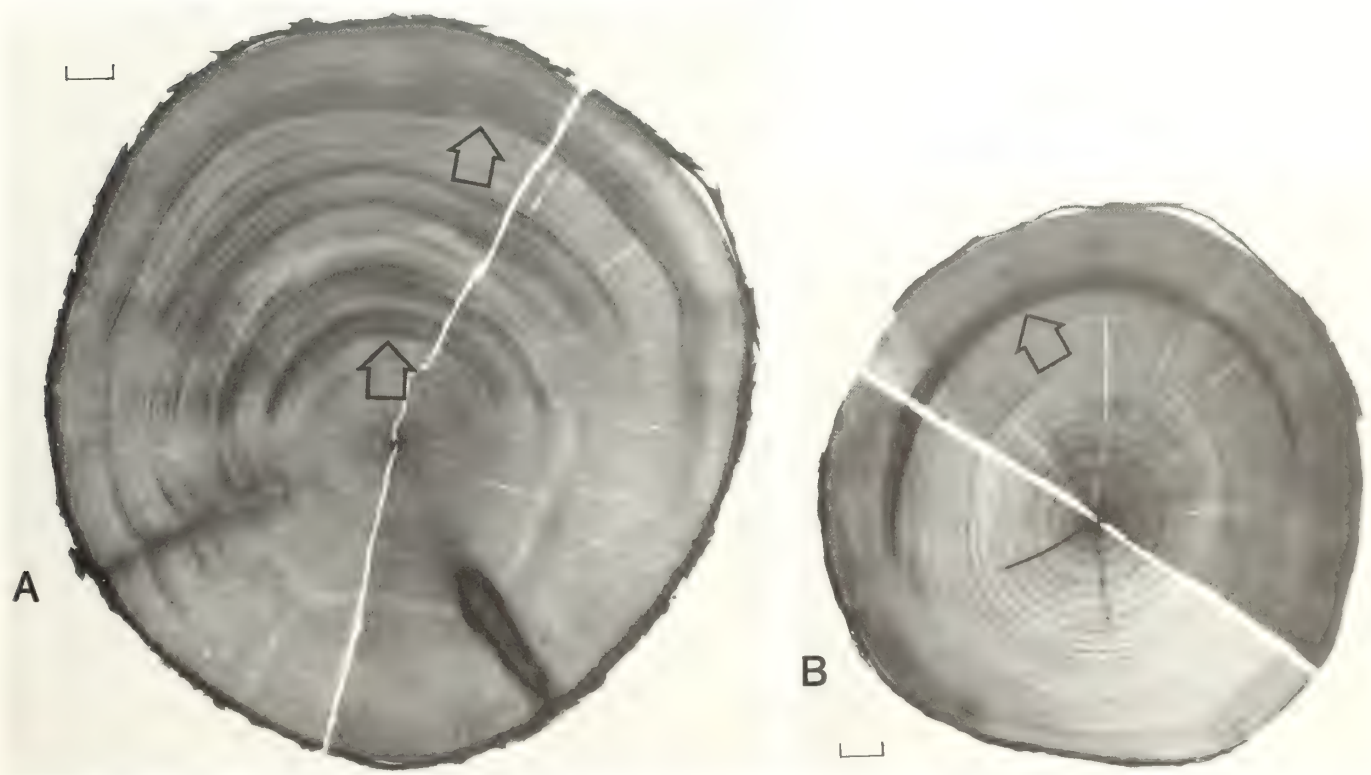


Figure 12—Frequently observed configuration of pattern #1 in lodgepole pine in which the compression wood has been formed in annular groupings during intermittent years. (A) Section at stump height from *latifolia* tree 152 mm in d.b.h. sampled at 45° latitude and medium elevation—replicate #1; multiple partial bands of compression wood. (B) Same tree sampled at 30 percent of tree height had only one band of compression wood. Scale mark shows 1 cm.

Table 4—Variation in percentage of four compression wood patterns in *latifolia* and *murrayana* transverse stem sections related to tree d.b.h.[1]

D.b.h.	1	2	3	4
mm		*Percent*		
		Latifolia		
76	51.4	9.5	11.1	28.0
152	47.3	5.8	8.3	38.6
228	42.2	12.1	8.5	37.2
Average	47.0	9.1	9.3	34.6
		Murrayana		
76	48.3	22.5	13.4	15.8
152	55.0	6.7	2.5	35.8
228	38.3	8.3	4.2	49.2
Average	47.2	12.5	6.7	33.6

[1]See figure 8 for pattern definitions. Data summarized from 2,430 sections of *latifolia*, and 360 sections of *murrayana*.

Pattern Variation With Latitude—With data on tree d.b.h. and elevational zones pooled, the percentage of the 2,430 *latifolia* sections with little or no compression wood was negatively correlated with latitude (tabulation following and fig. 13). Conversely, the percentage of sections with pattern #1 compression wood was positively correlated with latitude. Latitude was unrelated to percentage occurrence of compression wood patterns #2 and #3 in *latifolia* (fig. 13).

The 360 *murrayana* sections had different latitudinal variation; that is, percentages of sections with little or no compression wood were positively correlated with latitude (fig. 13), while percentages of sections with pattern #1 were negatively correlated with latitude as follows:

Latitude	Compression wood pattern 1	2	3	4
Degrees		*Percent*		
		Latifolia		
40	41.1	10.7	16.3	31.9
42.5	47.8	11.5	11.5	29.2
45	41.5	11.1	4.8	42.6
47.5	42.2	9.3	6.3	42.2
50	38.2	5.9	14.4	41.5
52.5	56.7	7.8	5.5	30.0
55	45.6	5.9	12.6	35.9
57.5	45.6	14.0	5.2	35.2
60	64.1	5.9	7.0	23.0
		Murrayana		
37.5	55.5	10.0	6.7	27.8
40	45.5	17.8	8.9	27.8
42.5	53.3	7.8	4.5	34.4
45	34.4	14.4	6.7	44.5

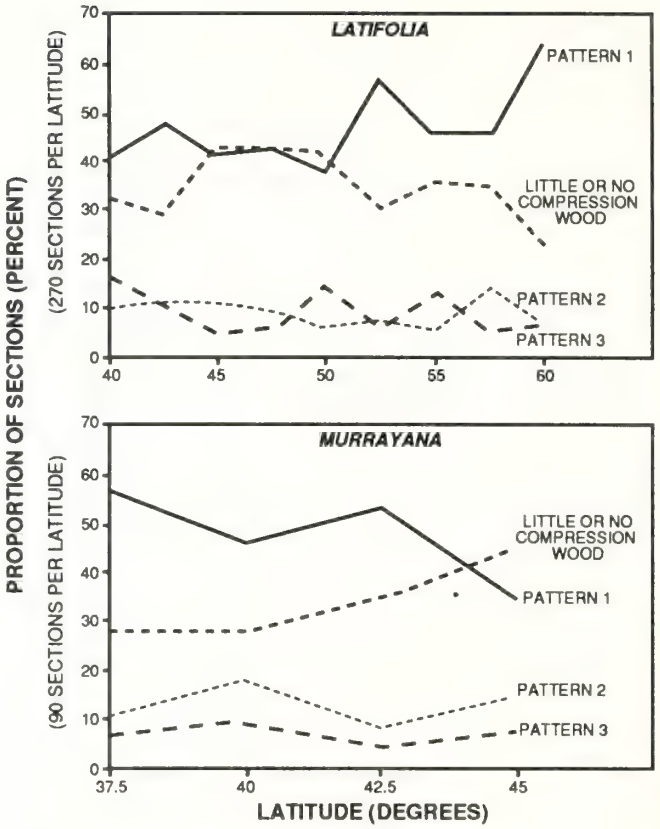


Figure 13—Compression wood patterns in transverse stem sections from 243 *latifolia* and 36 *murrayana* trees related to latitude. See figure 8 for pattern definitions.

In both varieties, sections sampled at 45 degrees through 50 degrees latitude had the greatest proportion of sections free of compression wood (fig. 13).

Pattern Variation With Height in Tree—In both *latifolia* and *murrayana* incidence of compression wood pattern #1 dominates near ground level, but incidence of this pattern diminishes with height in tree (fig. 14). Conversely, sections free of compression wood are infrequent in the lower stem, but upper stem sections are more frequently free of compression wood. Neither pattern #2 nor pattern #3 are descriptive of more than 20 percent of the sections analyzed, and correlation of these patterns' incidence with height is weak (fig. 14). Average values partitioned by percentage height in tree above a 152-mm-high stump top (with data on tree d.b.h., latitude, and elevational zone pooled) are summarized as follows:

Percentage of tree height	Compression wood pattern			
	1	2	3	4
	- - - - - - - - *Percent* - - - - - - - -			
	Latifolia			
0	62.1	5.8	8.6	23.5
10	56.4	10.3	13.2	20.1
20	56.0	6.2	11.1	26.7
30	52.7	8.2	12.4	26.7
40	46.9	8.2	9.1	35.8
50	44.4	5.4	12.8	37.4
60	40.3	9.9	9.1	40.7
70	38.3	11.9	7.0	42.8
80	37.4	10.3	6.6	45.7
90	35.0	15.2	3.3	46.5
	Murrayana			
0	69.4	2.8	16.7	11.1
10	61.1	11.1	13.9	13.9
20	50.0	16.7	8.3	25.0
30	55.5	13.9	5.6	25.0
40	44.4	16.7	8.3	30.6
50	50.0	13.9	2.8	33.3
60	27.8	16.7	5.5	50.0
70	50.0	8.3	0.0	41.7
80	41.7	11.1	0.0	47.2
90	22.2	13.9	5.6	58.3

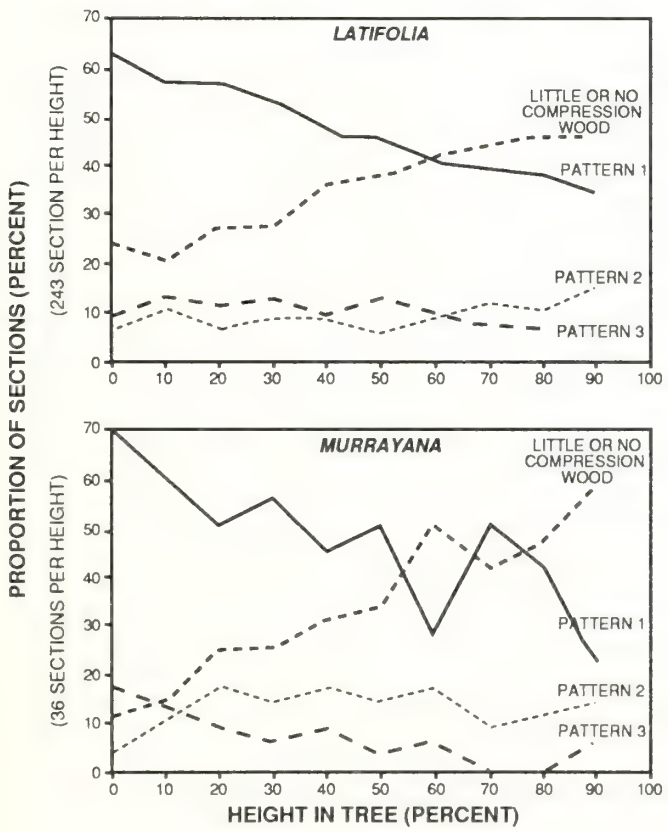


Figure 14—Compression wood patterns in transverse stem sections from 243 *latifolia* and 36 *murrayana* trees related to percentage height from 152-mm-high stump top to apical tip. See figure 8 for pattern definitions.

RESULTS—COMPRESSION WOOD CONTENT AND DISTRIBUTION

Knots and Compression Wood

In transverse sections of stems containing knots and viewed over a light table—or even under the light microscope—we found it extremely difficult to distinguish shadings caused by grain deviations from those caused by compression wood. Our impression is that adjacent to knot perimeters (viewed in stem transverse section) there is less compression wood present than the shading from light impedence suggests. The grain direction within the stemwood knots, and their resin content, precluded any light-table analysis of their compression wood content, and knot area was excluded from all totals of compression wood area in stem cross sections. Figure 15 is included to give the reader some idea of the grain distortions around lodgepole pine knots.

In comparing the compression wood content—by tree average—of sections with knots and sections without knots, the data are inconclusive as to whether presence of knots in cross sections increases or decreases the percentage of compression wood in the sections. Tree-average values of sections with no knots and sections with knots were as follows:

D.b.h.	No knots	Containing knots
mm	*Percent compression wood*	
	Latifolia	
76	7.3	5.7
152	3.7	2.8
228	4.8	4.3
All 243 trees	5.3	4.2
	Murrayana	
76	10.6	14.2
152	4.6	3.4
228	2.5	2.9
All 36 trees	5.9	7.0

The study was focused on transverse sections, but a few longitudinal sections through knots and pith were examined to confirm the impression that compression wood often forms in stems immediately below branches. Not always present, such compression wood was evident to some degree in about 30 percent of the longitudinal sections examined (fig. 16).

Surprisingly, tree-average percentage of compression-wood volume in stems of the 243 *latifolia* trees in the main study was negatively (and significantly) correlated with number of live and dead branches; that is, trees with least numbers of branches had most percentage of compression wood. The relationship was weak, however, accounting for only about 2 percent of the observed variation.

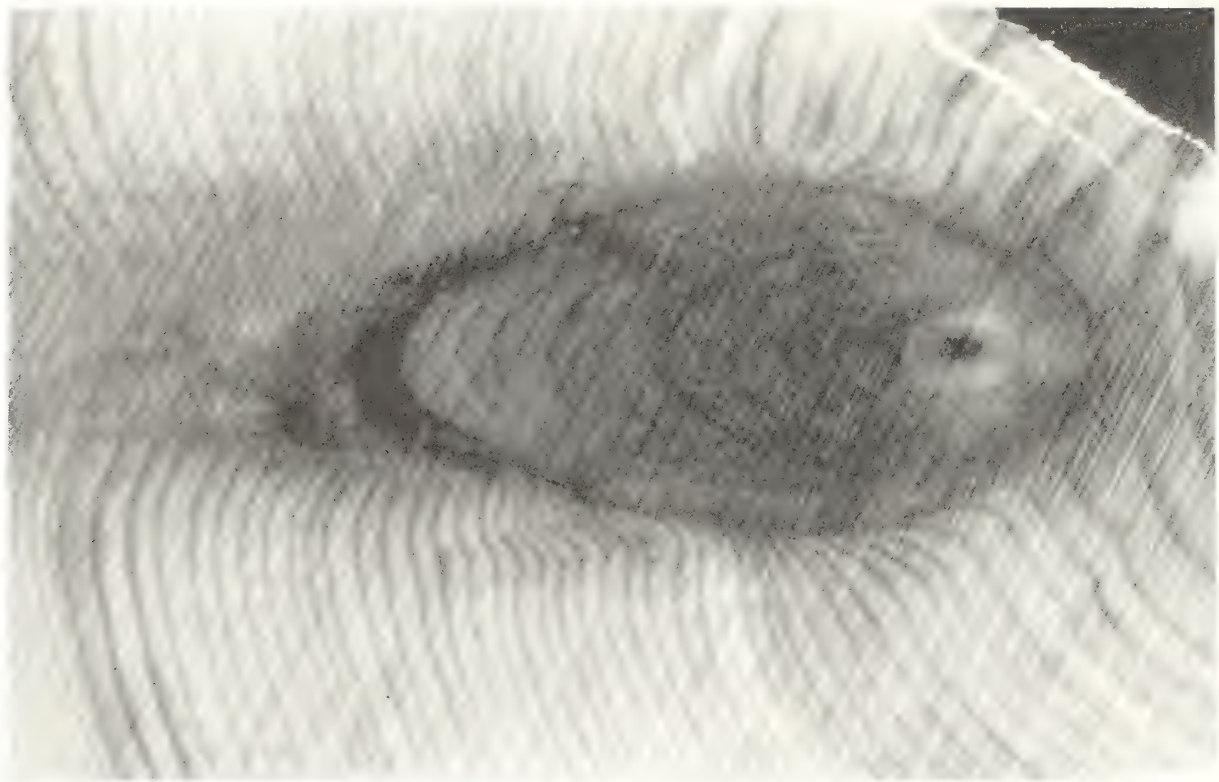


Figure 15—Transverse section through knot of *latifolia*. Grain deviations in vicinity of knot preclude accurate assessment of compression wood content by light-table method.

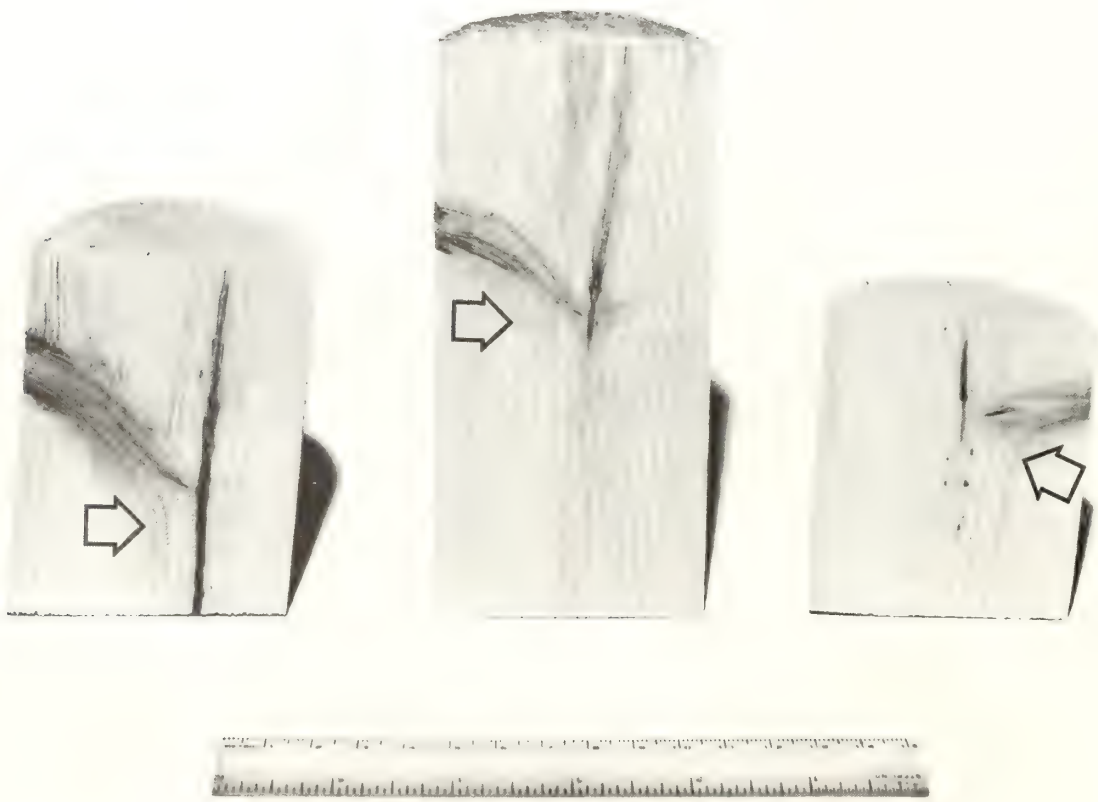


Figure 16—Longitudinal sections of *latifolia* showing compression wood (arrows) formed below branches. Sections measure about 65 mm in diameter.

Geographic Variation and Variation Among Trees by D.b.h. Class and Elevational Class—*Latifolia*

Trees 76 mm in d.b.h. had significantly higher stem-average percentage of compression wood than those 152 mm or 228 mm in d.b.h.; the 152-mm trees had the lowest percentage, as follows:

Tree d.b.h.	Number of trees	Compression wood content
mm		*Percent*
76	81	7.5
152	81	4.0
228	81	5.2

With data from trees of all diameters pooled, tree-average percentage compression wood did not vary significantly by elevational zone; averages were as follows:

Elevational zone	Percentage compression wood
Low	5.1
Medium	5.6
High	5.9

Similarly, with data from the 243 *latifolia* trees of all diameters and elevations pooled, tree-average percentage of compression wood did not differ significantly with latitude, as follows:

Latitude	Compression wood content
Degrees	*Percent*
40	5.6
42.5	5.3
45	3.8
47.5	6.0
50	5.6
52.5	6.1
55	7.2
57.5	4.7
60	5.6

There were no significant interactions among the three factors: d.b.h., elevational zone, and latitude. Table 5 summarizes the data by these three factors, displaying means, standard deviations, and ranges. With data from all 243 trees pooled, the mean tree-average percentage of compression wood was 5.5 percent, with range from 0.0 to 36.1 percent. Among these, only one stem was free of compression wood—a 152-mm tree from latitude 57.5 degrees in the low elevational zone (table 5).

Each sampling band (fig. 1) was 10 degrees of longitude wide and was divided into 10 longitudinal zones. Neither longitudinal zone nor longitude (degrees) was significantly correlated with percentage of compression wood.

Table 5—Mean, standard deviation, and range in tree-average percentage compression wood in stems of *latifolia* by latitude, elevational class, and tree d.b.h.[1]

Elevational class	Tree d.b.h.			
	76 mm	152 mm	228 mm	All trees
	Percent			
		40° Latitude		
Low	9.24 (8.58)	8.25 (9.64)	7.55 (2.44)	8.35 (6.61)
	3.8-19.1	1.2-19.2	4.7-9.0	1.2-19.2
Medium	5.28 (0.71)	2.35 (1.57)	2.96 (2.75)	3.53 (2.11)
	4.5-5.8	0.5-3.3	0.3-5.8	0.3-5.8
High	6.63 (5.04)	2.02 (1.58)	5.71 (4.71)	4.79 (4.12)
	3.3-12.4	0.3-3.5	1.8-10.9	0.3-12.4
		42.5° Latitude		
Low	5.04 (1.02)	5.54 (3.25)	3.43 (1.37)	4.67 (2.07)
	4.2-6.2	2.3-8.8	1.9-4.4	1.9-8.8
Medium	6.23 (7.65)	0.85 (0.88)	13.47 (12.7)	6.85 (9.23)
	0.7-15.0	0.3-1.9	2.7-27.5	0.3-27.5
High	6.45 (5.29)	1.54 (1.13)	4.77 (2.12)	4.25 (3.62)
	1.1-11.7	0.4-2.6	2.5-6.7	0.4-11.7
		45° Latitude		
Low	6.21 (0.84)	2.46 (2.52)	0.93 (0.43)	3.20 (2.71)
	5.5-7.1	0.7-5.3	0.6-1.4	0.6-7.1
Medium	7.52 (2.61)	3.50 (2.44)	2.42 (1.77)	4.48 (3.07)
	5.2-10.3	1.9-6.3	1.2-4.4	1.2-10.3
High	6.75 (7.41)	1.36 (0.82)	3.13 (1.49)	3.75 (4.48)
	0.9-15.1	0.6-2.2	1.4-4.1	0.6-15.1

(con.)

Table 5—(Con.)

Elevational class	Tree d.b.h. 76 mm	152 mm	228 mm	All trees
		Percent		
		47.5° Latitude		
Low	1.74 (0.82)	2.59 (1.90)	11.57 (9.38)	5.30 (6.73)
	1.2-2.7	0.6-4.3	1.2-19.4	0.6-19.4
Medium	8.07 (7.70)	5.74 (5.52)	7.18 (1.37)	7.00 (4.89)
	2.4-16.8	2.2-12.1	6.2-8.7	2.2-16.8
High	9.63 (10.77)	3.27 (0.90)	4.18 (3.94)	5.69 (6.48)
	2.1-22.0	2.2-3.8	1.2-8.6	1.2-22.0
		50° Latitude		
Low	3.98 (3.11)	1.82 (2.13)	4.56 (2.76)	3.45 (2.65)
	1.0-7.2	0.5-4.3	1.6-7.1	0.5-7.2
Medium	6.31 (5.25)	7.72 (5.39)	6.39 (4.66)	6.81 (4.48)
	1.2-11.7	1.7-12.0	2.3-11.5	1.2-12.0
High	10.22 (9.59)	1.92 (0.89)	7.12 (4.79)	6.42 (6.49)
	1.9-20.7	0.9-2.7	2.0-11.4	0.9-20.7
		52.5° Latitude		
Low	7.34 (5.35)	5.77 (4.79)	1.48 (0.58)	4.86 (4.46)
	2.3-13.0	1.7-11.0	1.1-2.2	1.1-13.0
Medium	10.03 (7.79)	5.77 (2.81)	5.46 (2.90)	7.09 (4.91)
	1.1-15.4	4.0-9.0	2.3-8.0	1.1-15.4
High	12.14 (5.90)	4.27 (3.84)	2.88 (0.67)	6.43 (5.58)
	7.6-18.8	0.8-8.4	2.2-3.5	0.8-18.8
		55° Latitude		
Low	4.93 (4.56)	8.84 (4.79)	9.92 (6.22)	7.90 (5.08)
	0.6-9.7	3.8-13.3	4.2-16.6	0.6-16.6
Medium	10.98 (5.86)	6.59 (3.43)	1.86 (1.09)	6.48 (5.24)
	4.3-15.4	3.7-10.4	1.0-3.1	1.0-15.4
High	9.52 (13.54)	8.37 (8.88)	3.64 (0.75)	7.18 (8.54)
	0.8-25.1	3.0-18.6	3.1-4.5	0.8-25.1
		57.5° Latitude		
Low	5.48 (1.27)	0.91 (1.43)	3.24 (2.75)	3.21 (2.59)
	4.5-6.9	0.0-2.6	0.9-6.3	0.0-6.9
Medium	5.07 (1.78)	3.85 (2.36)	4.06 (1.26)	4.33 (1.70)
	3.6-7.1	2.1-6.5	2.6-4.8	2.1-7.1
High	2.79 (0.68)	2.59 (3.1)	14.19 (19.01)	6.53 (11.22)
	2.1-3.5	0.5-6.2	2.2-36.1	0.5-36.1
		60° Latitude		
Low	10.29 (6.30)	2.36 (1.79)	1.59 (1.33)	4.75 (5.35)
	3.0-14.4	0.4-4.0	0.5-3.1	0.4-14.4
Medium	7.19 (2.34)	2.34 (1.02)	2.93 (3.59)	4.15 (3.18)
	5.2-9.8	1.3-3.3	0.7-7.1	0.7-9.8
High	16.13 (6.72)	4.06 (3.50)	3.32 (0.30)	7.84 (7.29)
	8.6-21.6	0.5-7.5	3.1-3.7	0.5-21.6
Pooled	7.45 (5.87)	3.95 (3.92)	5.18 (5.68)	5.53 (5.41)
	0.6-25.1	0.0-19.2	0.3-36.1	0.0-36.1

[1]Entries in the body of the table show the mean percentage, followed by the standard deviation in parentheses; listed below these two statistics is the range.

Identification of Trees That Will Have High Stem-Average Compression Wood Content—*Latifolia*

Although tree-average percentage of compression wood was not significantly related to geographic location (latitude, longitude, and elevation), it was significantly correlated (0.05 level) with many other tree characteristics, as follows:

Sign of correlation and characteristic	*r*
Positive	
Tree-average pith eccentricity (e), by d.b.h.	
76 mm	0.492
152 mm	.371
228 mm	.228
Tree-average e/r_1, all values	.336
Tree-average e/r_1, by d.b.h.	
76 mm	.484
152 mm	.325
228 mm	.284
Stemwood-average specific gravity	.324
r_1/r_2 (see fig. 9 for definition)	.319
Average live-branch angle	.233
e/r_1 (see fig. 9 for definition)	.230
Cone weight (computed from the number and weight of cones on the first foot of the top 25 branches) proportion of complete-tree weight, ovendry basis	.128
Stump-root proportion of complete-tree weight, ovendry basis	.126
Negative	
Average live-branch diameter	–0.181
Sapwood moisture content, stem-average	–.178
Stem diameter at base of live crown	–.173
Diameter at breast height	–.169
Diameter at 152-mm-high stump	–.167
Length of live crown	–.161
Heartwood diameter at top of 152-mm-high stump	–.160
Tree height from 152-mm-high stump top to apical tip	–.158
Stump–average bark thickness	–.155
Stembark thickness at 152-mm–high stump top	–.149
Number of dead branches	–.144
Number of live branches	–.142
Average width of annual rings at top of 152-mm-high stump	–.141
Branch proportion of complete-tree weight, ovendry	–.129

Also of interest is the **lack** of significant correlation between percentage of compression wood content in *latifolia* stems with the following tree characteristics:

Latitude
Longitude (degrees)
Longitudinal zone
Elevation (meters)
Age at stump top
Maximum stem crook
Stemwood-average out-of-roundness index; that is, minor/major diameter, average for 10 heights in each stem
Crown ratio
Width of live crown
Number of cones on first foot of top 25 branches
Total weight of live branches, ovendry (including bark, but not foliage)
Total stump-root weight including bark, ovendry
Total stemwood weight, ovendry
Total sapwood weight, ovendry
Total heartwood weight, ovendry
Complete-tree weight, ovendry
Bark proportion of complete-tree weight, ovendry
Foliage proportion of complete-tree weight, ovendry
Stemwood proportion of complete-tree weight, ovendry
Stembark-average specific gravity
Stembark-average moisture content
Stemwood-average moisture content
Heartwood moisture content
Moisture content of complete tree
Stem taper to base of live crown, millimeters per meter
Stem taper within live crown, millimeters per meter

When evaluating entire stems of *latifolia* trees, highest proportion of compression wood content will be found in slow-growing, small-diameter (for example, 76 mm), short trees with little heartwood at stump height, large live-branch angle, high stemwood specific gravity, and a relatively high proportion of complete-tree weight represented by the stump-root system and by cones. Because compression wood is more dense than "normal" wood, it is logical that stemwood-average specific gravity of trees with much compression wood should be higher than specific gravity in trees with little or no compression wood.

Lowest stem-average proportions of compression wood will be found in fast-growing, tall trees with long crowns, comprised of many branches, which typically have large diameter but small branch angle (and a relatively high proportion of complete-tree weight represented by branches), high sapwood moisture content, much heartwood at stump height, thick stump bark, and a low proportion of complete-tree weight represented by the stump-root system. Stemwood in such trees will have lower specific gravity than the stemwood of trees with a high proportion of compression wood.

Variation of Compression Wood Content Within Tree Stems—*Latifolia*

Compression wood content varied significantly with percentage of height in *latifolia* trees, the relationship differing by d.b.h. class (table 6 and figs. 17 and 18).

Table 6—Variation in *latifolia* and *murrayana* of percentage compression wood, out-of-roundness index, pith eccentricity, minor diameter, compression wood area, and gross cross-sectional area with percentage height in tree from 152-mm-high stump top to apical tip (see figure 9 for definitions)

D.b.h.	Percentage of tree height									
	0	10	20	30	40	50	60	70	80	90
mm										
					Latifolia					
					Compression wood content (percent)					
76	11.1	8.7	7.3	5.8	6.3	5.2	5.3	6.0	7.3	6.3
152	5.2	5.2	4.3	3.7	2.9	2.7	2.5	2.1	2.9	4.0
228	6.0	7.5	5.9	5.4	3.5	2.9	3.9	2.9	3.9	5.4
					Out-of-roundness index					
76	0.88	0.91	0.92	0.92	0.92	0.92	0.91	0.91	0.89	0.87
152	.88	.91	.92	.92	.92	.92	.91	.91	.90	.88
228	.87	.91	.92	.92	.92	.92	.91	.91	.90	.90
					Pith eccentricity, *e* (mm)					
76	7.4	5.0	3.9	3.6	3.4	2.8	2.4	2.0	1.6	0.9
152	12.5	9.0	7.1	7.2	6.2	5.7	5.1	4.0	3.0	2.2
228	20.2	14.8	13.4	11.8	10.3	9.8	9.1	6.7	4.8	3.2
					e/r_1					
76	0.16	0.12	0.10	0.10	0.10	0.09	0.09	0.09	0.09	0.09
152	.13	.11	.10	.10	.10	.10	.10	.09	.09	.10
228	.14	.12	.12	.11	.11	.11	.11	.10	.10	.11
					r_1/r_2					
76	1.56	1.35	1.30	1.29	1.29	1.26	1.24	1.26	1.26	1.20
152	1.43	1.32	1.27	1.27	1.26	1.24	1.26	1.25	1.25	1.28
228	1.41	1.35	1.32	1.30	1.28	1.28	1.30	1.26	1.26	1.28
					Minor diameter (mm)					
76	69.1	65.7	62.8	59.0	54.6	49.4	43.2	35.7	27.0	16.0
152	142.1	128.4	121.5	114.3	107.6	98.4	87.7	73.5	56.9	33.0
228	215.5	192.9	182.3	172.5	159.2	145.6	129.4	108.4	81.8	46.5
					Compression wood area (mm^2)					
76	482	325	247	172	164	107	86	71	48	16
152	942	740	541	416	291	232	173	102	84	44
228	2,507	2,416	1,680	1,377	750	528	589	293	224	112
					Gross cross-sectional area of wood (mm^2)					
76	4,317	3,750	3,400	2,996	2,588	2,129	1,641	1,129	669	249
152	18,267	14,285	12,690	11,260	9,914	8,280	6,691	4,772	2,891	1,050
228	42,722	32,249	28,498	25,441	21,920	18,199	14,688	10,320	5,956	1,978
					Murrayana					
					Compression wood content (percent)					
76	22.7	17.6	15.6	10.0	12.8	7.3	5.5	9.2	4.6	9.1
152	10.0	8.2	2.6	3.4	3.0	2.3	2.8	1.6	6.4	2.1
228	6.4	2.6	2.2	2.7	3.5	2.0	.8	1.4	1.7	3.2
					Out-of-roundness index					
76	0.88	0.90	0.93	0.91	0.91	0.89	0.91	0.89	0.89	0.88
152	.87	.91	.92	.92	.92	.92	.91	.92	.91	.90
228	.86	.93	.92	.92	.92	.91	.91	.91	.92	.90
					Pith eccentricity, *e* (mm)					
76	9.3	6.8	6.3	4.1	3.8	2.9	2.2	2.0	0.9	0.6
152	19.3	8.9	8.1	6.0	5.6	5.7	4.3	3.0	2.8	1.3
228	22.6	13.1	12.4	13.8	9.7	7.8	7.1	6.4	2.6	1.9
					e/r_1					
76	0.20	0.16	0.16	0.11	0.12	0.10	0.09	0.10	0.07	0.08
152	.18	.11	.11	.09	.09	.10	.09	.08	.09	.09
228	.14	.11	.11	.13	.11	.09	.09	.10	.06	.08

(con.)

Table 6—(Con.)

D.b.h.	Percentage of tree height									
	0	10	20	30	40	50	60	70	80	90
mm										
					r_1/r_2					
76	1.76	1.49	1.48	1.34	1.34	1.26	1.22	1.30	1.24	1.17
152	1.78	1.36	1.29	1.23	1.26	1.27	1.23	1.20	1.29	1.18
228	1.57	1.29	1.35	1.36	1.25	1.24	1.25	1.31	1.12	1.20
					Minor diameter (mm)					
76	66.4	64.0	62.8	58.1	52.9	46.1	39.4	31.2	22.7	13.2
152	139.6	128.6	120.8	112.3	103.3	92.8	79.9	66.2	49.5	27.4
228	214.8	193.3	181.2	169.8	156.1	140.3	122.8	101.6	73.6	39.1
					Compression wood area (mm^2)					
76	895	647	541	303	325	141	75	78	20	14
152	1,926	1,178	328	362	273	177	181	53	115	7
228	2,940	804	627	666	742	336	106	125	67	42
					Gross cross-sectional area of wood (mm^2)					
76	4,008	3,635	3,391	2,940	2,468	1,916	1,380	875	461	166
152	17,912	14,301	12,481	10,832	9,204	7,474	5,644	3,859	2,210	700
228	42,623	31,702	28,250	24,696	20,815	17,113	13,150	9,090	4,736	1,447

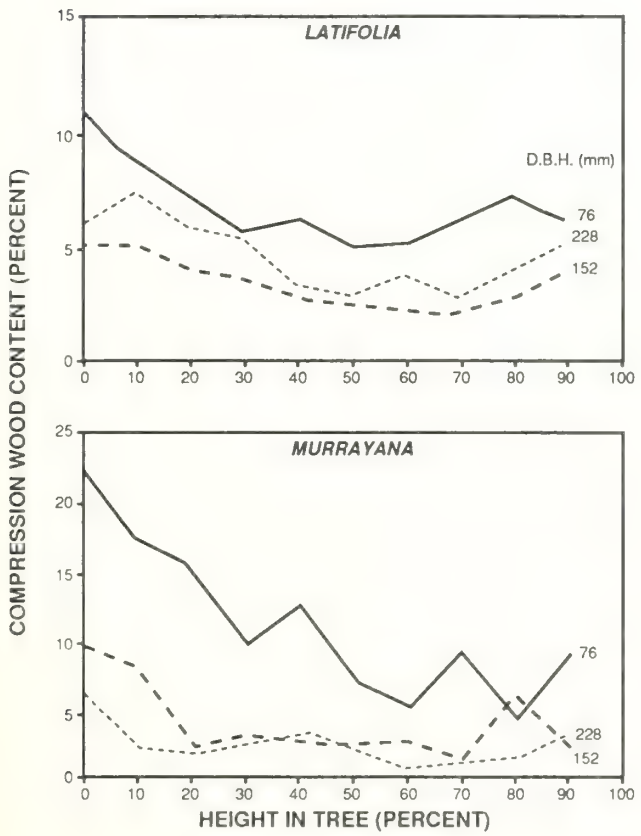


Figure 17—Variation of compression wood content with height in stems of *latifolia* (81 of each d.b.h.) and *murrayana* (12 of each d.b.h.) trees of three diameters.

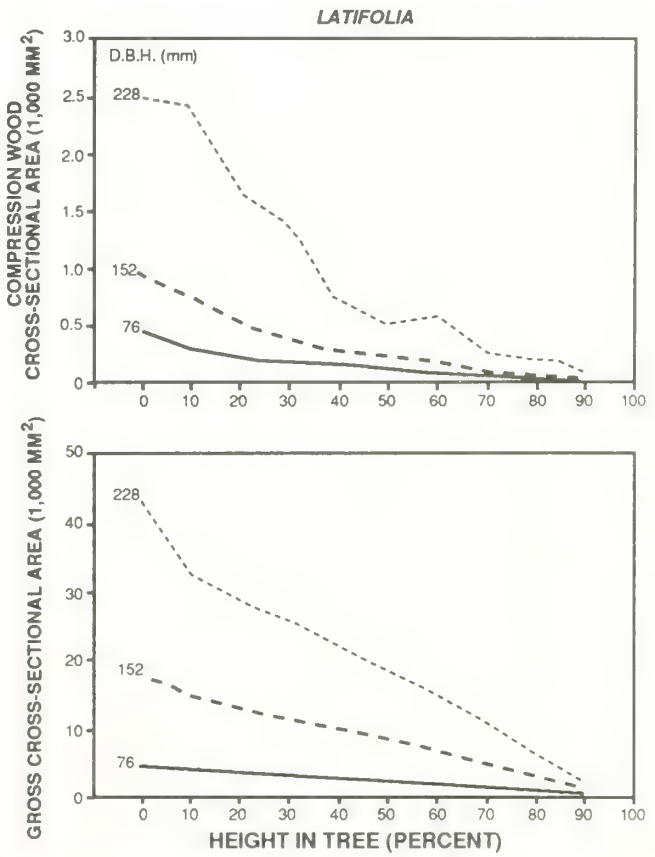


Figure 18—Variation with height in tree of compression wood cross-sectional area and gross cross-sectional area (bark-free) in *latifolia* trees of three diameters. See table 6 for numeric values.

When the percentage compression wood content of each of the 2,430 (243 trees x 10 heights) *latifolia* sections was correlated—and each of the 360 *murrayana* sections similarly correlated—with each section's other properties, some significant relationships were evident, as follows:

Section's characteristic correlated with the section's percentage of compression wood	*Latifolia* (n = 2.430) r	*Murrayana* (n = 360) r
Positive correlations		
r_1/r_2 (fig. 19)	0.378	0.518
e/r_1 (fig. 19)	.362	.489
Specific gravity of wood (fig. 20)	.299	.409
Pith eccentricity, e (fig. 20)	.187	.230
Negative correlations		
Out-of-roundness index (fig. 20)	–0.180	–0.188
Height above ground, meters	–.150	–.370
Moisture content of wood	–.136	–.309
Minor diameter	–.040	–.171

These correlations suggest that sections (or short logs) sampled in *latifolia* stems will tend to have high percentages of compression wood if they are out of round and close to ground level, and have eccentric piths, high specific gravities, and low moisture contents. Also, there is a weak tendency for small-diameter wood to have more percentage compression wood content than large-diameter wood.

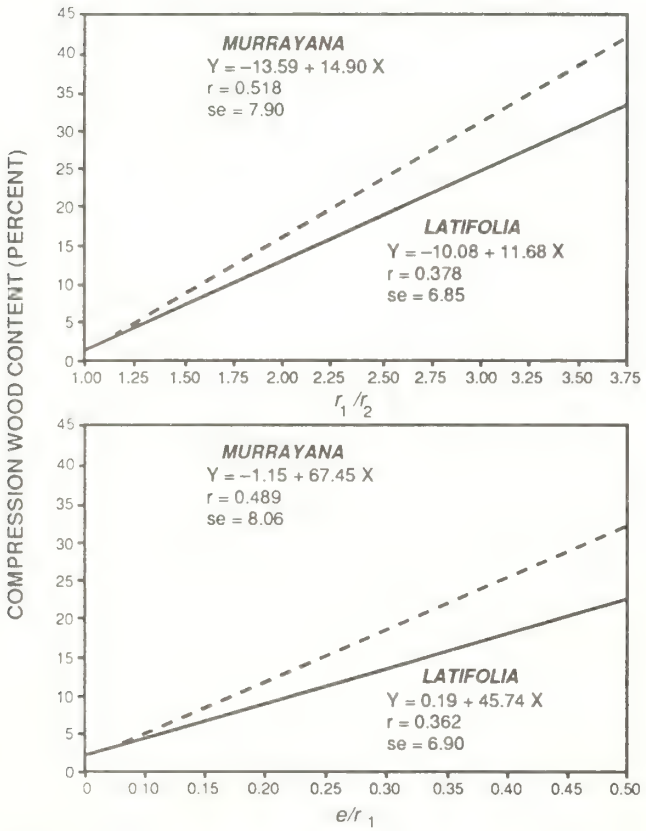


Figure 19—Regression equations relating compression wood content of individual stem sections in *latifolia* (n = 2,430) and *murrayana* (n = 360) to two measures of pith eccentricity (e/r_1 and r_1/r_2).

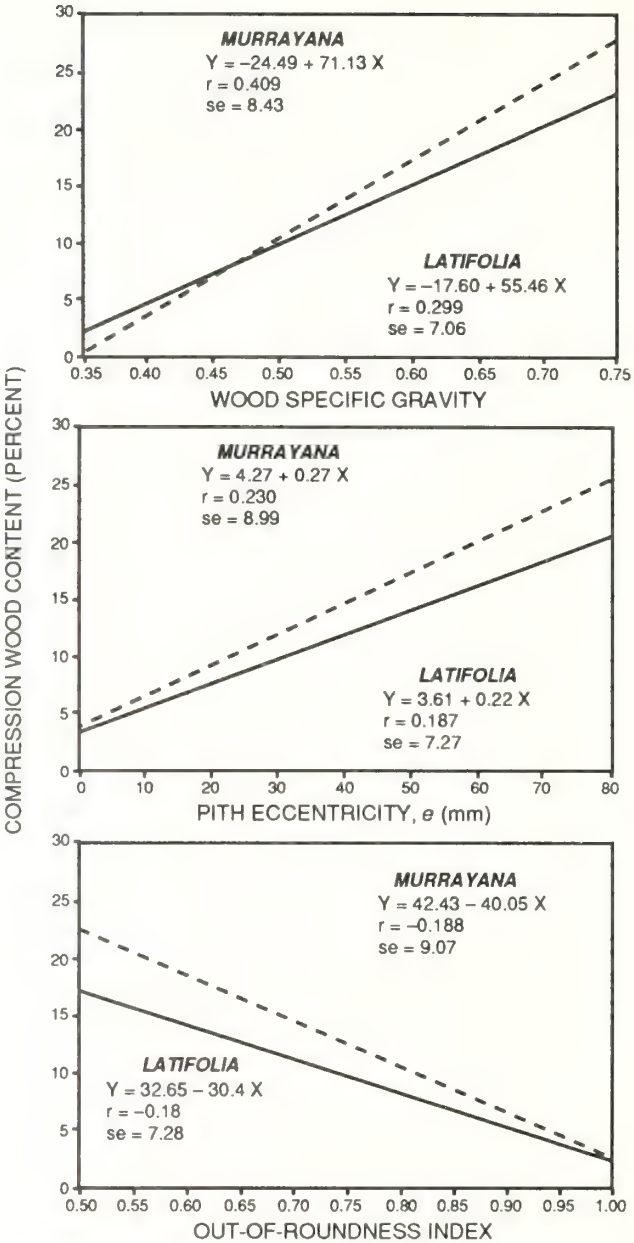


Figure 20—Regression equations for three section characteristics significantly related to compression wood content of individual stem sections in *latifolia* (n = 2,430) and *murrayana* (n = 360) trees. Wood specific gravity is based on green volume and ovendry weight.

Location of Sections Free of Compression Wood—See previous discussion of pattern #4 occurrence under heading "Results—General Observations and Anatomy".

Location Within Section Where Compression Wood Will Probably Be Concentrated—Analysis of all the sections that did contain compression wood indicated that the location of the major areas of compression wood in a section or log end—though not easily distinguishable visually—can usually be predicted. That is, a line projected from the pith through the center of the largest

circle that can be inscribed within the section will usually pass through the main area of compression wood on the r_1 side or on both the r_1 and r_2 sides (fig. 9), as follows:

Description of line intersection with compression wood area	*Latifolia*	*Murrayana*
	Percent	
Intersection on r_1 side only (fig. 9, right)	61.8	68.6
Intersection on r_2 side only	5.5	5.1
Intersection on both r_1 and r_2 sides	18.1	17.8
Line did not intersect compression wood areas on either r_1 or r_2 side	14.6	8.5
	100.0	100.0

Thus—with data on d.b.h. classes pooled—the line depicted in figure 9 (right) passed through a major area of compression wood on the r_1 side (or on both the r_1 and r_2 sides) in 79.9 percent of those sections with compression wood in *latifolia* and 86.4 percent of the *murrayana* sections that contained compression wood.

These proportions varied with d.b.h., however, as follows:

D.b.h.	*Latifolia*	*Murrayana*
mm	*Percent*	
r_1 intersection (or both r_1 and r_2 intersections)		
76	86.8	94.1
152	85.4	83.1
228	68.8	80.0
Line did not intersect compression wood areas on either r_1 or r_2 side		
76	7.9	2.0
152	9.8	10.4
228	24.9	15.0

As noted previously, compression wood is extremely difficult to detect visually on exposed log ends under woods or mill conditions. Log sections that probably contain compression wood can be identified, however; see figures 19 and 20 with associated discussion. In such logs, a sawyer can predict that compression wood present will probably lie along the line depicted in figure 9b—and most likely be on the r_1 side. With this knowledge, the sawyer may be able to place the compression wood where it will be least damaging in the product he is manufacturing.

Variation Among Trees by D.b.h. Class and Latitude —*Murrayana*

Variety *murrayana* trees 76 mm in d.b.h. had significantly higher stem-average percentage of compression wood than those 152 mm or 228 mm in d.b.h. Compression-wood content was negatively correlated with d.b.h. as follows:

Tree d.b.h.	Number of trees	Compression wood content
mm		*Percent*
76	12	14.3
152	12	5.5
228	12	3.3
Average		7.7

With data from the 36 *murrayana* trees pooled, tree-average percentage of compression wood did not differ significantly with latitude, as follows:

Latitude	Compression wood content
Degrees	*Percent*
37.5	8.2
40	9.6
42.5	5.4
45	7.6

There were no significant interactions between d.b.h. and latitude. With data from all 36 trees pooled, the mean tree-average percentage of compression wood was 7.7 percent, with range from 0.1 to 26.2 percent. No tree of variety *murrayana* was found free of compression wood (table 7).

Variation of Compression Wood Content Within Stems—*Murrayana*

Percentage of compression wood content varied significantly with percent height in *murrayana* trees, the relationship differing with d.b.h. class (figs. 17 and 21; and table 6).

As noted under the discussion of variation of compression wood content within *latifolia* trees (and tabulation of correlation coefficients), stem sections or short logs

Table 7—Mean, standard deviation, and range in tree-average percentage compression wood in stems of *murrayana* by latitude, and tree d.b.h.[1]

Latitude	Tree d.b.h. 76 mm	152 mm	228 mm	All trees
Degrees	*Percent*			
37.5	16.97 (8.34)	5.10 (5.42)	2.40 (0.38)	8.16 (8.35)
	10.1-26.2	2.0-11.4	2.2-2.8	2.0-26.2
40	12.04 (7.79)	10.49 (2.20)	6.40 (2.26)	9.64 (4.90)
	4.1-19.7	8.3-12.7	4.5-8.9	4.1-19.7
42.5	10.87 (9.43)	3.88 (0.77)	1.41 (0.65)	5.38 (6.37)
	1.7-20.6	3.0-4.4	0.8-2.0	0.8-20.6
45	17.14 (10.01)	2.61 (1.22)	3.04 (4.66)	7.60 (9.06)
	6.1-25.5	1.4-3.8	0.1-8.4	0.1-25.5
Pooled	14.25 (8.17)	5.52 (4.05)	3.31 (2.97)	7.69 (7.20)
	1.7-26.2	1.4-12.7	0.1-8.9	0.1-26.2

[1]Entries in the table show the mean percentage, followed by the standard deviation in parentheses; listed below these two statistics is the range.

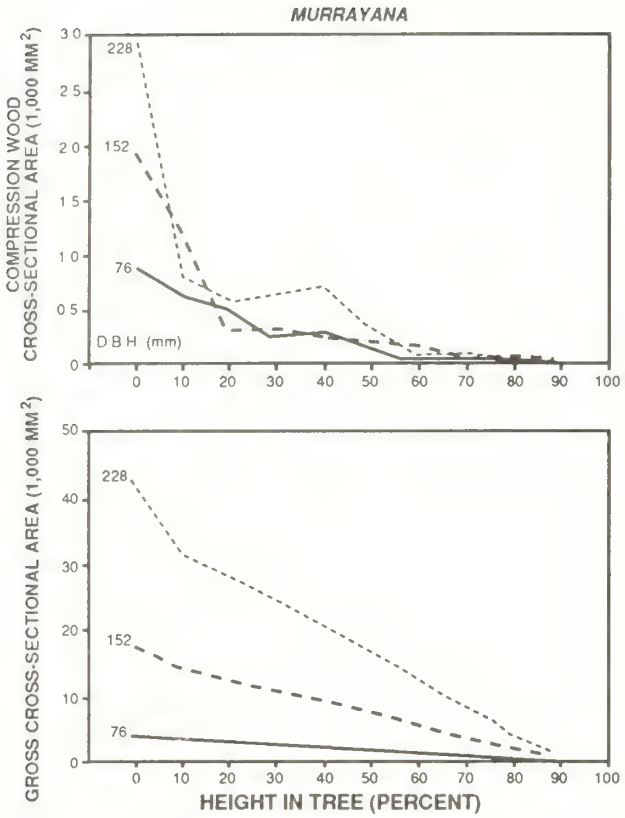


Figure 21—Variation with height in tree of compression wood cross-sectional area and gross cross-sectional area (bark-free) of *murrayana* trees of three diameters. See table 6 for numeric values.

sampled from *murrayana* trees will tend to contain a high percentage of compression wood if they are out of round and close to the ground, and have eccentric piths, high specific gravities, low moisture contents, and small minor diameters (figs. 19 and 20).

Location of Sections Free of Compression Wood—See previous discussion of pattern #4 occurrence under heading "Results—General Observations on Anatomy."

Location Within Section Where Compression Wood Will Probably Be Concentrated—See preceding discussion of *latifolia* under this same paragraph heading.

Compression Wood in *Latifolia* Compared to *Murrayana*

Variety *murrayana* (all 36 trees) averaged significantly more compression wood than variety *latifolia* (all 243 trees) with averages (tables 5, 6, and 7) as follows:

Tree d.b.h.	*Murrayana*	*Latifolia*
mm	------ *Percent* ------	
76	14.3	7.5
152	5.5	4.0
228	3.3	5.2
Average	7.7	5.5

Varietal differences in the proportions of trees in discrete compression-wood content classes were also significant (fig. 22).

When compared only at the latitudes (40, 42.5, and 45 degrees) and elevational zone (medium) the two samples had in common, tree-average percent compression wood was significantly greater in *murrayana* trees 76 mm and 152 mm in d.b.h. than in *latifolia* trees of these diameters, as follows:

Tree d.b.h.	*Murrayana*	*Latifolia*
mm	------ *Percent* ------	
76	13.4	6.3
152	5.7	2.2
228	3.6	6.3
Average	7.6	4.9

As noted previously, percentage of compression wood content in individual stem sections of *murrayana* was more strongly correlated with out-of-roundness, proximity to ground, pith eccentricity, wood specific gravity, wood moisture content, and disk diameter than was compression wood content in *latifolia*.

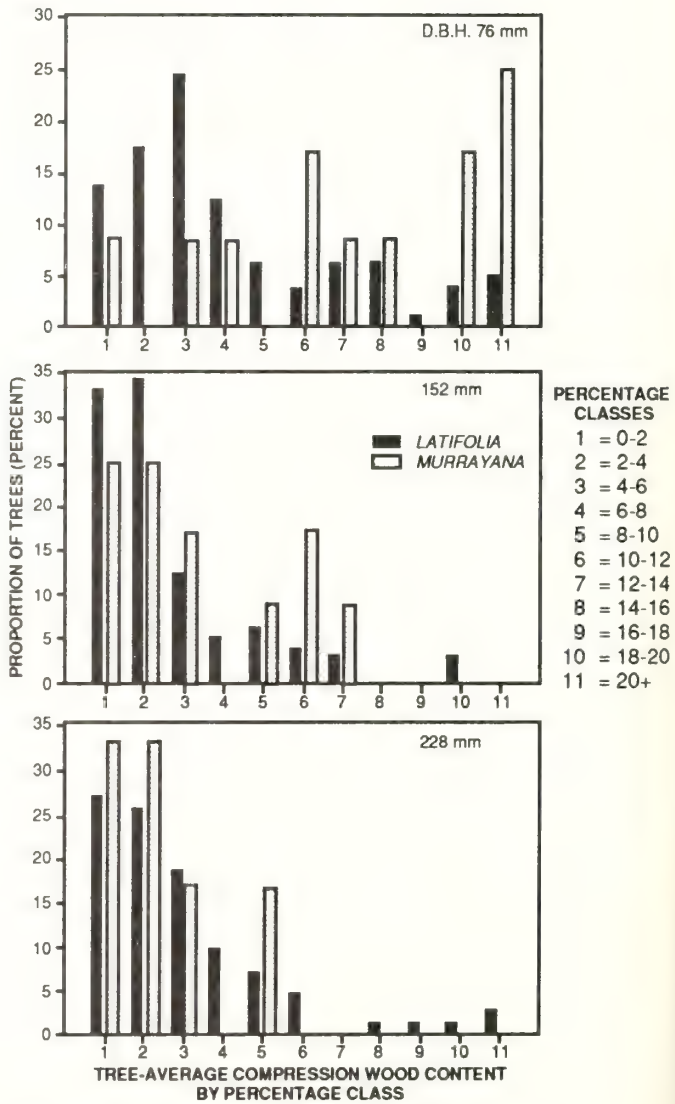


Figure 22—Frequency distribution of tree-average compression-wood content in *latifolia* and *murrayana* trees of three diameters. Data are based on 81 *latifolia* and 12 *murrayana* trees of each d.b.h.

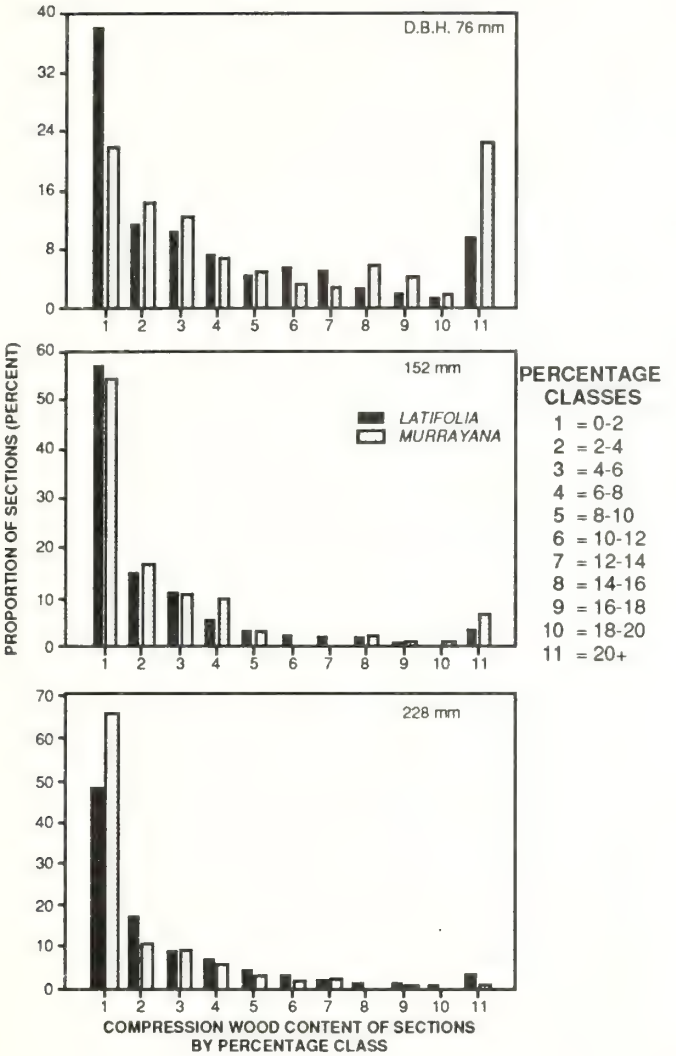


Figure 23—Frequency distribution of individual section's (disk's) compression-wood content in *latifolia* and *murrayana* trees of three diameters. Sections were taken at each tenth of tree height. Number of sections in each of the three d.b.h. classes was 810 for *latifolia* and 120 for *murrayana*.

With all sections of all trees from all latitudes considered, significant varietal differences by height were apparent (fig. 17), as were differences in the proportions of sections in discrete compression-wood content classes (fig. 23).

RESULTS—OUT-OF-ROUNDNESS INDEX

Geographic Variation and Variation Among Trees by D.b.h. Class and Elevational Class—*Latifolia*

Surprisingly, tree-average out-of-roundness index for bark-free stems (fig. 9) was not significantly correlated with tree-average compression-wood content. When individual sections taken at 10-percent height increments were considered, however, out-of-roundness index was negatively correlated with compression wood content as discussed in previous text; that is, tree stem sections that are out of round tend to have a high percentage of compression wood.

Additionally, stem out-of-roundness has considerable influence on optimum sawing patterns and lumber yield—and for this reason is now examined in detail.

The mean value (243 trees) for tree-average out-of-roundness index was 0.908. This value did not vary significantly with tree d.b.h. (table 8) or with elevational zone. It did, however vary significantly with latitude, as follows:

Latitude	Out-of-roundness index
Degrees	
40	0.911
42.5	.912
45	.917
47.5	.905
50	.914
52.5	.903
55	.916
57.5	.897
60	.895

Table 8—Comparison by d.b.h. class of measures of tree-average out-of-roundness and pith eccentricity between varieties *latifolia* and *murrayana*, with data from all latitudes pooled, and with data pooled only from those latitudes and the elevational class common to the two varieties (see figure 9 for definitions)

Tree d.b.h., mm	Out-of-roundness index		*e*		*e*/*r*[1]		r_1/r_2	
	Latifolia	*Murrayana*	*Latifolia*	*Murrayana*	*Latifolia*	*Murrayana*	*Latifolia*	*Murrayana*
				All latitudes				
76	0.907	0.901	3.3	3.9	0.10	0.12	1.30	1.36
152	.908	.913	6.2	6.5	.10	.10	1.28	1.31
228	.909	.910	10.4	9.7	.11	.10	1.31	1.29
Average	.908	.908	6.6	6.7	.11	.11	1.30	1.32
				Latitude 40, 42.5, and 45 degrees				
76	0.912	0.901	2.8	3.8	0.10	0.11	1.24	1.35
152	.918	.910	5.4	6.1	.09	.09	1.24	1.29
228	.910	.917	9.2	10.3	.11	.11	1.30	1.30
Average	.913	.909	5.8	6.7	.10	.10	1.26	1.31

These data suggest that tree stems are most nearly circular in average cross section in those latitudinal zones from 40 degrees to 55 degrees (with the exception of zones at 47.5 degrees and 52.5 degrees), and are more elliptical in the northernmost zones of 57.5 and 60 degrees.

There were no significant interactions among the three factors: d.b.h., elevational zone, and latitude.

As noted previously, the 243-tree average was 0.908; standard deviation was 0.02, with range in out-of-roundness index from 0.82 to 0.94. This range suggests that although tree stems may have nearly circular cross sections at some level above ground, tree-average sections are considerably out of round.

Identification of Trees That Will Have Out-of-Round Stems—*Latifolia*

Although tree-average out-of-roundness index was not significantly related to tree d.b.h. or elevational zone, it was significantly correlated (0.05 level) with many other tree characteristics, as follows:

Sign of correlation and tree characteristic	*r*
Positive	
Stemwood moisture content	0.267
Moisture content of complete tree	.262
Moisture content of sapwood	.214
Elevation, feet	.181
Number of live branches	.167
Stembark moisture content	.153
Average annual ring width at stump top	.137
Negative	
r_1/r_2 (fig. 9)	–0.335
Latitude (degrees)	–.234
Longitude (degrees)	–.198
Stembark specific gravity	–.197
Stemwood specific gravity	–.189
e (fig. 9)	–.166
Average live branch angle (degrees)	–.147
e/r_1 (fig. 9)	–.131
Tree age at stump (years)	–.154
Bark percentage of complete-tree ovendry weight	–.140
Maximum stem crook	–.132

These correlations suggest that in addition to the latitude relationships previously noted (and the longitude correlation because of the longitudinal skew of the sample zones as shown in figure 1), entire stems of *latifolia* are likely to average most circular in cross section in fast-growing young trees of high moisture content, low specific gravity, with pith not eccentric, little stem crook, low bark percentage of complete-tree ovendry weight, and with many live branches making a small angle with the stem above them. Because latitude is inversely correlated with meters of elevation, trees at higher elevations may have stems more nearly circular in cross section than those at lowest elevations.

Variation Within Tree Stems—*Latifolia*

Out-of-roundness index varied significantly with percent height in *latifolia* trees, the relationship differing by d.b.h. class (table 6). With all data pooled, it appears that in both varieties, stems are most nearly circular in cross section near midheight (fig. 24).

When out-of-roundness index of each of the 2,430 (243 trees x 10 heights) *latifolia* sections was correlated—and each of the 360 *murrayana* sections similarly correlated—with each section's other properties, some significant relationships were evident, as follows:

Section's characteristic correlated with the section's out-of-roundness index	*Latifolia* (*n* = 2,430) *r*	*Murrayana* (*n* = 360) *r*
Positive correlations		
Minor diameter	0.084	N.S.
Moisture content of wood	.059	0.110
Negative correlations		
r_1/r_2 (fig. 25)	–0.274	–0.283
e/r_1 (fig. 25)	–.256	–.218
Percentage compression wood content	–.180	–.188
Specific gravity of wood	–.178	–.209
Pith eccentricity, *e*	–.173	–.201

These correlations suggest that sections (or short logs) sampled in *latifolia* stems will tend to be out of round if they contain much compression wood or have eccentric piths, high specific gravity, small minor diameter, and low moisture content; the last two relationships, although statistically significant, are weak.

Out-of-roundness index was not significantly correlated with height above ground.

Variation Among Trees by D.b.h. Class and Latitude—*Murrayana*

Variety *murrayana* bark-free stems had tree-average out-of-roundness index of 0.91, with standard deviation of 0.03 and range from 0.81 to 0.94. Values did not differ significantly with latitude or diameter class; there was no significant latitude x diameter interaction. Averages by diameter class are summarized as follows:

D.b.h. *mm*	*n*	Mean	Standard deviation	Range
76	12	0.901	0.033	0.81-0.94
152	12	.913	.023	.86-.94
228	12	.910	.024	.84-.93

With data for trees of all three diameters pooled, tree-average values by latitude were as follows:

Latitude *Degrees*	*n*	Mean	Standard deviation	Range
37.5	9	0.903	0.027	0.84-0.92
40	9	.903	.037	.81-.93
42.5	9	.911	.026	.86-.94
45	9	.913	.015	.89-.94

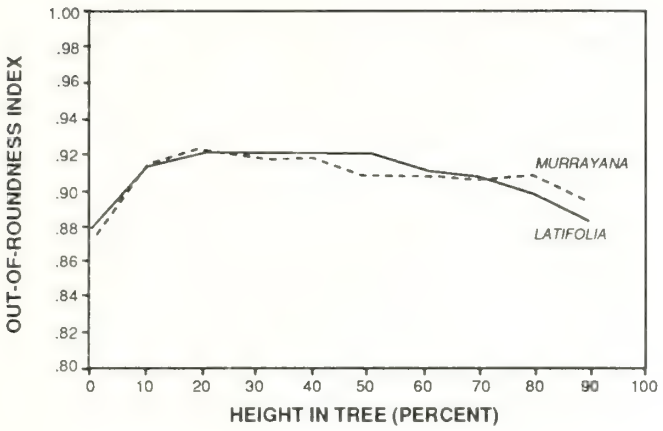


Figure 24—Variation in out-of-roundness index (bark-free) with height in trees of *latifolia* (243 trees) and *murrayana* (36 trees); all data pooled.

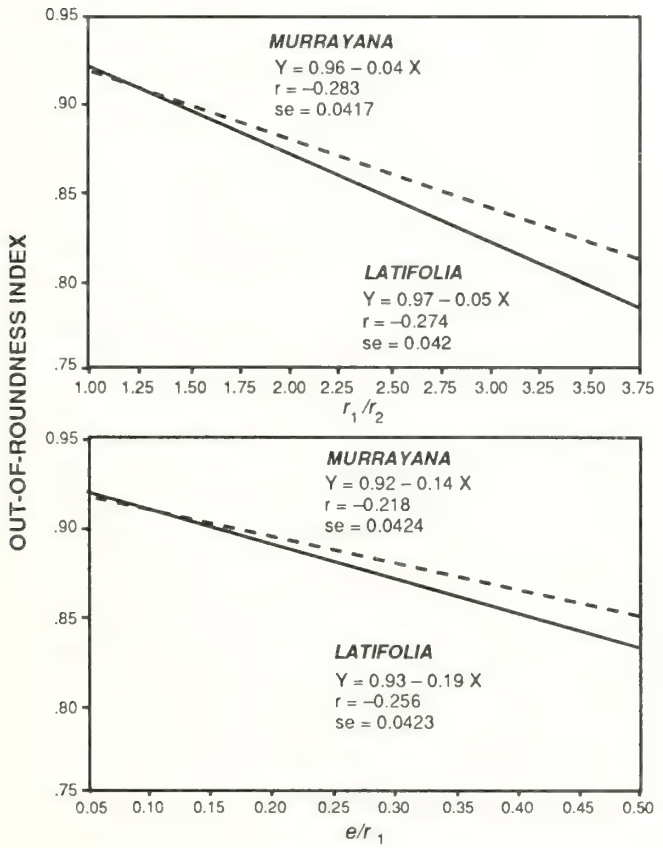


Figure 25—Regression equations relating out-of-roundness index of individual stem sections of *latifolia* (n = 2,430) and *murrayana* (n = 360) to two measures of pith eccentricity (e/r_1 and r_1/r_2).

Variation Within Tree Stems—*Murrayana*

Out-of-roundness varied significantly with percent height in *murrayana* trees (fig. 24), the relationship differing by d.b.h. class (table 6).

As noted under the discussion of variation of out-of-roundness index within *latifolia* trees (and tabulation of correlation coefficients), stem sections or short logs sampled from *murrayana* stems will tend to be out of round if they contain much compression wood or have eccentric piths, high specific gravity, and low moisture content.

Out-of-Roundness Index of *Latifolia* Compared to *Murrayana*

Tree-average out-of-roundness index did not differ significantly between *murrayana* and *latifolia* (fig. 24); see table 8 for average values. This was true for all-latitude comparisons as well as comparisons at the latitudes and elevations sampled in common.

With all sections of all trees from all latitudes considered, however, significant varietal differences in the proportions of sections in discrete out-of-roundness classes were apparent (fig. 26).

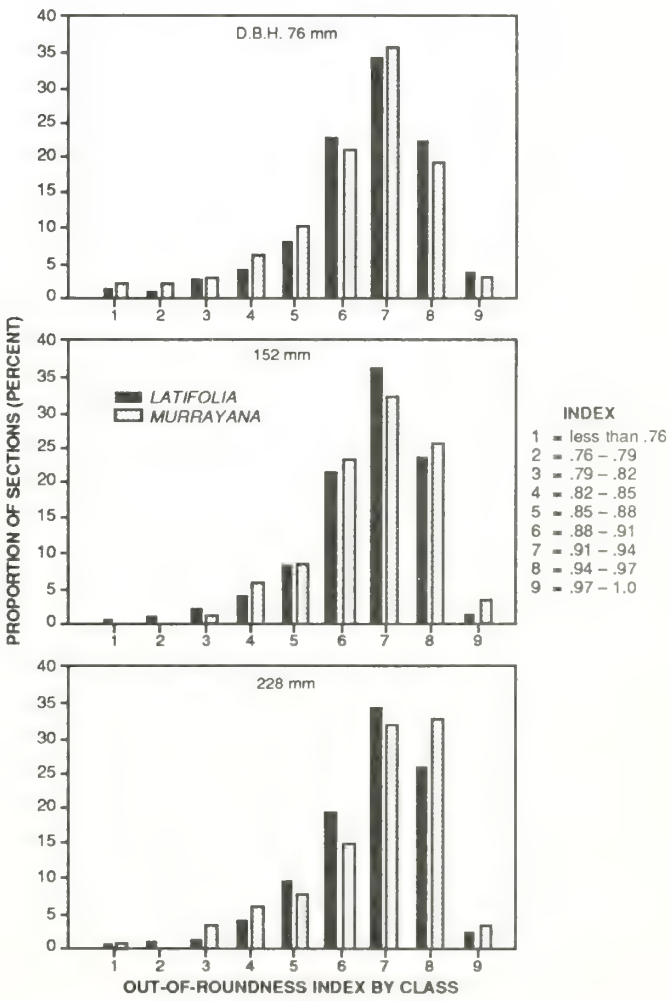


Figure 26—Frequency distribution of individual section's (disk's) out-of-roundness index in *latifolia* and *murrayana* trees of three diameters. Sections were taken at each tenth of tree height. Number of sections in each of the three d.b.h. classes was 810 for *latifolia* and 120 for *murrayana*.

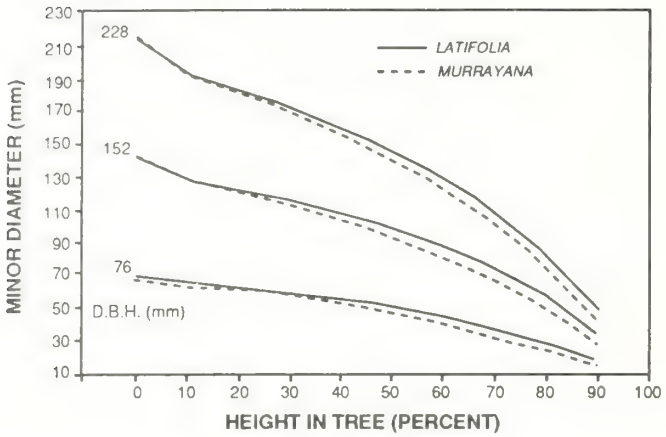


Figure 27—Variation with height in tree of minor diameter (fig. 9) of bark-free stems of *latifolia* and *murrayana* trees of three diameters. See table 6 for numeric values.

Minor Diameters of *Latifolia* Compared to *Murrayana*—Bark-Free

Minor-diameter variation with height in tree (table 6) is important to manufacturers of roundwood products—particularly dowelled products. Minor diameter is related to both stem taper and out-of-roundness. In trees of comparable d.b.h., and at comparable percentages of tree height, upper *murrayana* stems have slightly smaller minor diameters than *latifolia* stems (fig. 27).

RESULTS—MEASURES OF PITH ECCENTRICITY

Three characteristics that provide a measure of pith eccentricity seem useful: e, e/r_1, and r_1/r_2, as defined in figure 9. Following is a discussion of these characteristics by variety.

Latifolia—*e*

Geographic Variation and Variation Among Trees by D.b.h. Class and Elevational Class—With data from all 243 trees pooled, tree-average pith eccentricity (e) averaged 6.63 mm, with standard deviation of 3.92 mm and range from 0.50 mm to 25.0 mm. Large trees had significantly greater average pith eccentricity than small trees (fig. 28), with no significant d.b.h. interactions with latitude or elevational zone, as follows:

D.b.h.	Mean	Standard deviation	Range
		mm	
76	3.3	1.3	0.5-7.6
152	6.2	2.1	2.3-10.4
228	10.4	3.8	4.6-25.0

Pith eccentricity averaged least in the medium elevational zone (6.2 mm) and was greater at low elevation (6.6 mm) and at high elevation (7.1 mm). At latitudes 42.5, 52.5, and 57.5 degrees, however, low-zone trees had less pith eccentricity than medium (table 9).

Pith eccentricity averaged less (5.5-6.3 mm) in intermediate latitudinal zones of 45 to 52.5 degrees than in more southerly and more northerly latitudes (6.8-8.0 mm). See table 9.

The variation with d.b.h., latitude, and elevational zone seems sufficient to tabulate pith eccentricty (e) partitioned by these factors (table 10).

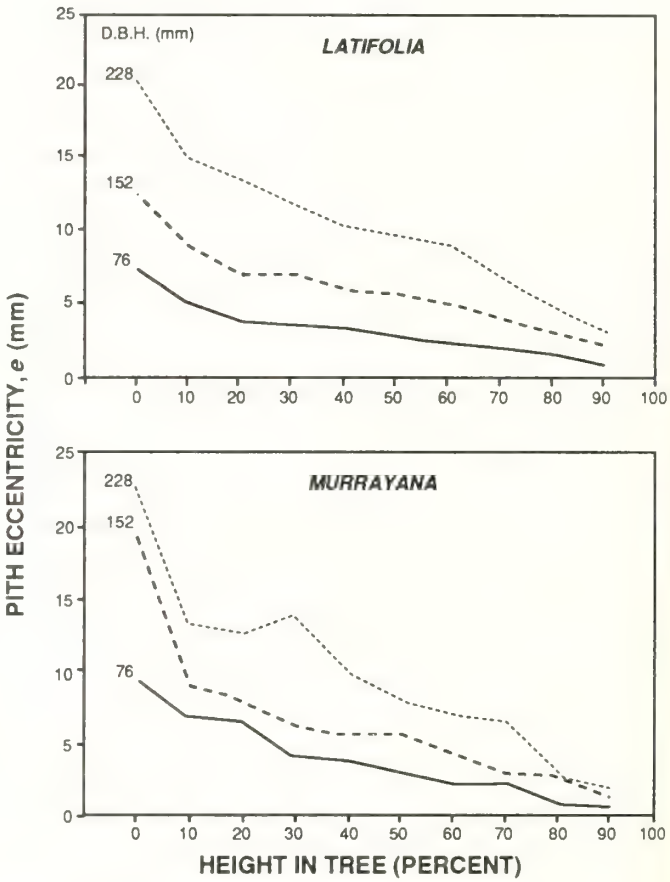


Figure 28—Variation of pith eccentricity (e) with height in stems of *latifolia* (81 of each d.b.h.) and *murrayana* (12 of each d.b.h.) trees of three diameters.

Table 9—Variation of tree-average pith eccentricity (e) in *latifolia* related to latitude and elevational zone.

Latitude	Elevational zone: Low	Medium	High	Average
Degrees		*mm*		
40	8.7	6.1	6.4	7.1
42.5	6.1	6.7	7.8	6.9
45	6.0	4.6	5.9	5.5
47.5	6.0	5.5	6.5	6.0
50	6.0	4.9	7.5	6.1
52.5	4.5	6.9	7.6	6.3
55	7.5	6.4	6.6	6.8
57.5	5.9	7.4	7.9	7.1
60	8.6	7.8	7.7	8.0
Average	6.6	6.2	7.1	6.6

Table 10—Mean, standard deviation, and range in tree-average pith eccentricity (*e*) in stems of *latifolia* by latitude, elevational class, and tree d.b.h.[1]

Elevational class	Tree d.b.h. 76 mm	152 mm	228 mm	All trees
		Millimeters		
		40° Latitude		
Low	3.77 (1.92)	9.17 (1.33)	13.17 (1.37)	8.70 (4.30)
	1.7-5.5	7.7-10.3	11.6-14.1	1.7-14.1
Medium	3.33 (1.14)	4.87 (0.55)	10.23 (0.64)	6.14 (3.22)
	2.4-4.6	4.3-5.4	9.5-10.6	2.4-10.6
High	2.50 (0.17)	6.13 (2.28)	10.67 (0.55)	6.43 (3.73)
	2.3-2.6	4.1-8.6	10.3-11.3	2.3-11.3
		42.5° Latitude		
Low	3.20 (1.28)	7.63 (1.76)	7.37 (1.91)	6.07 (2.59)
	2.1-4.6	5.8-9.3	5.6-9.4	2.1-9.4
Medium	2.47 (0.83)	6.17 (3.84)	11.47 (2.11)	6.70 (4.51)
	1.8-3.4	2.9-10.4	10.2-13.9	1.8-13.9
High	2.63 (0.75)	5.10 (1.13)	15.70 (8.54)	7.81 (7.41)
	1.9-3.4	3.8-5.8	8.2-25.0	1.9-25.0
		45° Latitude		
Low	4.03 (0.91)	7.10 (1.47)	6.73 (2.25)	5.96 (2.03)
	3.2-5.0	5.8-8.7	4.8-9.2	3.2-9.2
Medium	2.53 (0.67)	5.23 (2.04)	5.90 (1.35)	4.56 (2.00)
	2.1-3.3	2.9-6.7	4.8-7.4	2.1-7.4
High	3.53 (0.47)	3.67 (1.34)	10.47 (5.51)	5.89 (4.46)
	3.0-3.9	2.7-5.2	6.8-16.8	2.7-16.8
		47.5° Latitude		
Low	1.87 (0.40)	5.37 (2.32)	10.80 (3.90)	6.01 (4.52)
	1.4-2.1	2.9-7.5	6.8-14.6	1.4-14.6
Medium	3.23 (1.37)	5.37 (1.10)	7.83 (4.65)	5.48 (3.19)
	2.3-4.8	4.1-6.1	5.0-13.2	2.3-13.2
High	4.37 (1.71)	6.17 (3.59)	9.07 (3.80)	6.53 (3.43)
	2.4-5.5	3.9-10.3	5.3-12.9	2.4-12.9
		50° Latitude		
Low	2.47 (0.59)	5.57 (1.54)	10.00 (3.25)	6.01 (3.75)
	1.8-2.9	3.8-6.6	7.6-13.7	1.8-13.7
Medium	2.00 (0.82)	5.03 (2.70)	6.43 (0.40)	4.89 (2.43)
	1.3-2.9	2.3-7.7	6.0-6.8	1.3-7.7
High	2.80 (0.44)	4.83 (0.72)	14.93 (3.86)	7.52 (5.96)
	2.3-3.1	4.0-5.3	11.2-18.9	2.3-18.9
		52.5° Latitude		
Low	2.70 (0.92)	4.17 (0.57)	6.50 (1.68)	4.46 (1.94)
	1.9-3.7	3.7-4.8	4.6-7.8	1.9-7.8
Medium	3.37 (0.35)	7.00 (1.37)	10.27 (0.67)	6.88 (3.09)
	3.0-3.7	5.5-8.2	9.5-10.7	3.0-10.7
High	5.70 (1.68)	6.63 (1.72)	10.50 (2.86)	7.61 (2.89)
	4.4-7.6	4.7-8.0	7.2-12.2	4.4-12.2
		55° Latitude		
Low	2.67 (0.60)	8.23 (1.01)	11.67 (2.72)	7.52 (4.20)
	2.1-3.3	7.3-9.3	8.6-13.8	2.1-13.8
Medium	3.63 (1.18)	5.27 (2.10)	10.23 (1.86)	6.38 (3.34)
	2.9-5.0	3.1-7.3	8.1-11.5	2.9-11.5
High	3.93 (1.31)	7.83 (1.86)	7.93 (2.20)	6.57 (2.53)
	2.7-5.3	6.3-9.9	5.4-9.3	2.7-9.9
		57.5° Latitude		
Low	2.40 (1.71)	4.50 (0.75)	10.90 (4.71)	5.93 (4.60)
	0.5-3.8	3.7-5.2	7.2-16.2	0.5-16.2
Medium	3.10 (1.51)	7.93 (2.25)	11.10 (3.93)	7.38 (4.23)
	1.7-4.7	5.4-9.7	6.8-14.5	1.7-14.5
High	4.00 (0.61)	7.10 (1.91)	12.47 (3.18)	7.86 (4.16)
	3.6-4.7	5.9-9.3	8.9-15.0	3.6-15.0

(con.)

Table 10—(Con.)

Elevational class	Tree d.b.h. 76 mm	152 mm	228 mm	All trees
	Millimeters			
	60° Latitude			
Low	5.77 (1.50)	7.20 (2.94)	12.77 (2.11)	8.58 (3.75)
	4.1-7.0	3.8-8.9	11.0-15.1	3.8-15.1
Medium	3.37 (0.76)	7.17 (2.40)	12.87 (4.93)	7.80 (4.98)
	2.5-3.9	5.4-9.9	7.2-16.2	2.5-16.2
High	3.37 (0.12)	6.57 (1.72)	13.17 (3.35)	7.70 (4.72)
	3.3-3.5	4.6-7.8	9.3-15.2	3.3-15.2
	Pooled			
Low	3.29 (1.29)	6.19 (2.11)	10.41 (3.78)	6.63 (3.92)
	0.5-7.6	2.3-10.4	4.6-25.0	0.5-25.0

[1]Entries in the table show the mean value, followed by the standard deviation in parentheses; listed below these two statistics is the range.

Identification of *Latifolia* Trees That Will Have Eccentric Piths—Tree-average pith eccentricity (e) was not only significantly related to geographic location, elevational zone, and d.b.h., but was also significantly correlated (0.05 level) with many other tree characteristics, as follows:

Sign of correlation and tree characteristic	r
Positive	
D.b.h.	0.743
Diameter at 152-mm-high stump top	.739
Total stump-root weight including bark, ovendry	.698
Complete-tree weight, ovendry	.697
Heartwood diameter at 152-mm-high stump top	.696
Total stem weight including bark, ovendry	.674
Total stemwood weight, ovendry	.670
Average live branch diameter	.657
Foliage weight, ovendry	.647
Stem diameter at base of live crown	.639
Sapwood weight, ovendry	.634
Live branch weight with bark, ovendry	.612
Heartwood weight	.597
Width of live crown	.580
Tree height to apical tip	.555
Total number of cones on first foot of top 25 branches	.553
Stem taper within live crown, millimeters per meter	.550
Age at stump top	.530
Branch bark thickness	.463
Average bark thickness of stump	.439
Number of live branches	.395
Stem taper from stump top to base of live crown, millimeters per meter	.394
Stembark thickness at top of 152-mm-high stump	.392
Taproot length	.381
Dead branch weight, ovendry	.375
Number of dead branches	.371
Length of live crown	.327
Branchwood proportion of ovendry complete-tree weight	.272
Stembark specific gravity	.260
Average ring width at 152-mm-high stump top	.259
Cone weight proportion of complete-tree ovendry weight	.216
Moisture content of sapwood, percent of ovendry weight	.206
Stemwood proportion of ovendry complete-tree weight	.167
Maximum stem crook	.142
Negative	
Tree bark proportion of ovendry complete-tree weight	–0.428
Stembark moisture content, percent of ovendry weight	–.381
Stump-root wood proportion of ovendry complete-tree weight	–.346
Moisture content of heartwood, percent of ovendry weight	–.289
Stemwood specific gravity	–.188
Foliage proportion of ovendry complete-tree weight	–.188
Tree-average out-of-roundness index	–.166
Crown ratio	–.133
Moisture content of complete tree, percent of ovendry weight	–.131

These correlation coefficients indicate that tree-average pith eccentricity (e) is greatest in fast-growing, large-diameter, tall trees with sapwood of low moisture content. Surprisingly, stem crook was not a strongly related factor (r = +0.142). The negative correlation coefficients suggest that tree-average pith eccentricity is least in trees of high moisture content in heartwood and stembark, and high tree-average out-of-roundness index (those most circular in cross section).

Variation of Pith Eccentricity (e) Within *Latifolia* Trees—Pith eccentricity varied significantly with percent height in *latifolia* trees, the relationship differing by d.b.h. class (fig. 28 and table 6).

When pith eccentricity of each of the 2,430 (243 trees x 10 heights) *latifolia* sections was correlated—and each of the 360 *murrayana* sections similarly correlated—with other properties of each section, some significant relationships were evident, as follows:

Section's characteristic correlated with the section's pith eccentricity (*e*)	*Latifolia* (*n* = 2,430) *r*	*Murrayana* (*n* = 360) *r*
Positive correlations		
e/r_1	0.712	0.725
Major diameter (fig. 29)	.637	.699
r_1/r_2	.623	.779
Percentage compression wood (fig. 29)	.187	.230
Wood specific gravity	.123	N.S.
Negative correlations		
Height above ground, meters (fig. 30)	–0.287	–0.307
Moisture content of wood (fig. 30)	–.248	–.213
Out-of-roundness index	–.173	–.201

These correlations suggest that a section (or short log) sampled in a *latifolia* stem will tend to have large pith eccentricity if it is large in diameter, out of round, and in the lower stem portion, and if it has large compression wood content, high specific gravity, and low moisture content.

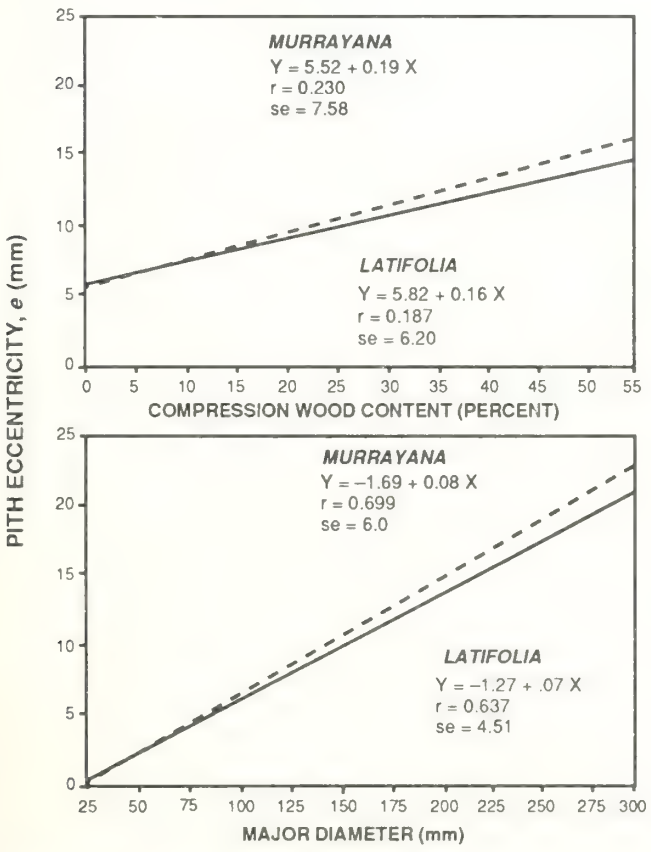


Figure 29—Regression equations relating pith eccentricity (*e*) of individual stem sections of *latifolia* and *murrayana* trees to compression wood content and major diameter of the sections. The equations are based on 2,430 and 360 sections, respectively.

Murrayana—e

Among *Murrayana* Trees—Pith eccentricity (*e*) in *murrayana* averaged 6.70 mm, with standard deviation of 3.75 mm and range from 2.0 mm to 15.7 mm (table 11). This eccentricity did not vary significantly with latitude, but was positively correlated with d.b.h., as follows:

D.b.h.	*e*
------ *mm* ------	
76	3.9
152	6.5
228	9.7

Within *murrayana* Trees—Pith eccentricity (*e*) varied significantly with percent height in *murrayana* trees, the relationship differing by d.b.h. class (fig. 28 and table 6).

As noted under the discussion of pith eccentricity within *latifolia* trees—and accompanying tabulation of correlation coefficients—a stem section (or short log) sampled from a *murrayana* tree will tend to have large pith eccentricity if it is large in diameter, out of round, and in the lower stem portion, and if it has a large compression wood content and low moisture content (figs. 29 and 30).

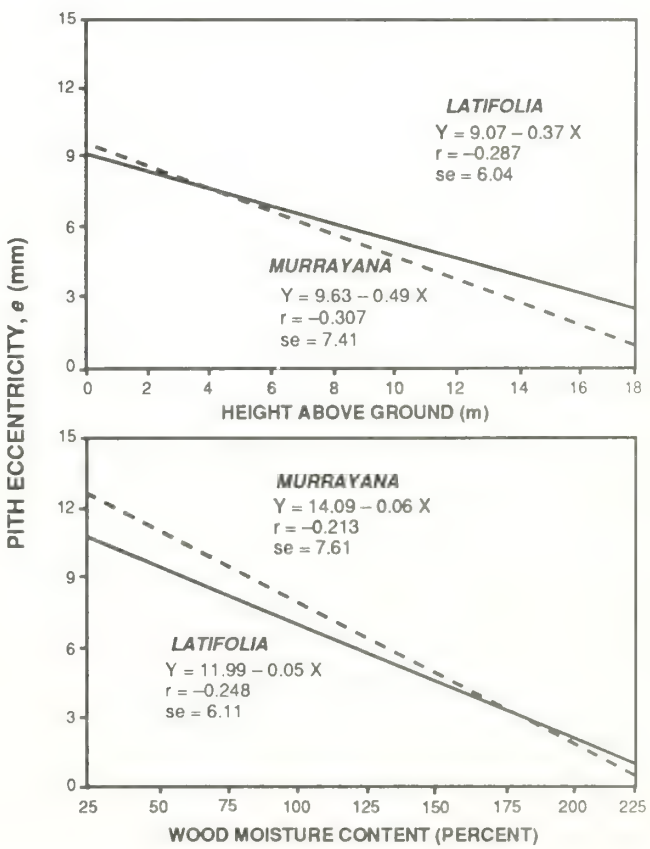


Figure 30—Regression equations relating pith eccentricity (*e*) of individual stem sections of *latifolia* and *murrayana* trees to wood moisture content and height above ground of each section. The equations are based on 2,430 and 360 sections, respectively.

Table 11—Mean, standard deviation, and range in tree-average pith eccentricity (e) in stems of *murrayana* by latitude and tree d.b.h.[1]

Latitude	Tree d.b.h. 76 mm	152 mm	228 mm	All trees
Degrees	*Millimeters*			
37.5	4.00 (1.65)	7.50 (2.01)	8.00 (2.62)	6.50 (2.64)
	2.9-5.9	5.2-8.9	5.6-10.8	2.9-10.8
40	5.13 (2.56)	7.37 (2.76)	10.23 (4.75)	7.58 (3.75)
	2.2-6.9	5.3-10.5	7.1-15.7	2.2-15.7
42.5	3.23 (0.75)	8.00 (0.95)	11.70 (4.80)	7.64 (4.43)
	2.8-4.1	7.4-9.1	6.3-15.5	2.8-15.5
45	3.17 (1.39)	3.07 (0.59)	9.03 (5.17)	5.09 (4.00)
	2.0-4.7	2.4-3.5	5.8-15.0	2.0-15.0
Pooled	3.88 (1.68)	6.48 (2.58)	9.74 (4.06)	6.70 (3.75)
	2.0-6.9	2.4-10.5	5.6-15.7	2.0-15.7

[1]Entries in the table show the mean value, followed by the standard deviation in parentheses; listed below these two statistics is the range.

Pith Eccentricity (e) of *Latifolia* Compared to That of *Murrayana*

No significant differences between the two varieties were found in tree-average pith eccentricity (e); see table 8. As noted previously, pith eccentricity in individual stem sections of *murrayana* was more strongly correlated with section diameter, out-of-roundness, height above ground, and percentage compression wood (but not wood moisture content and specific gravity) than pith eccentricity in *latifolia* was correlated with these characteristics in individual stem sections (figs. 29 and 30).

Latifolia—e/r_1

A high value of the ratio e/r_1 indicates a high degree of pith eccentricity and out-of-roundness (fig. 9). Of all the factors evaluated, the ratio e/r_1 was best correlated with percentage of compression wood in individual sections (fig. 19).

Geographic Variation and Variation Among D.b.h. Classes and Elevational Classes—Tree-average values for the ratio e/r_1 averaged 0.11 for *latifolia*, with standard deviation of 0.03 and range from 0.02 to 0.22. Trees 152 mm in d.b.h. did not vary significantly with either latitude or elevational class (average 0.11). Trees 76 mm and 228 mm in d.b.h. did vary significantly, however, in an elevational class x latitude interaction (table 12). These data suggest that trees with lowest ratios will be found at medium elevation from latitude 45 degrees through 50 degrees, or at low elevation from 47.5 degrees through 52.5 degrees.

Table 12—Tree-average means for *latifolia* of ratio e/r_1 related to latitude, d.b.h., and elevational class

D.b.h.	Elevational class: Low	Medium	High	Averages
mm				
		40° Latitude		
76	0.13	0.11	0.09	0.11
152	.15	.09	.10	.11
228	.13	.12	.11	.12
All				.11
		42.5° Latitude		
76	.10	.09	.09	.09
152	.12	.10	.09	.10
228	.09	.13	.15	.12
All				.10
		45° Latitude		
76	.12	.09	.10	.10
152	.11	.09	.06	.09
228	.09	.07	.12	.09
All				.09
		47.5° Latitude		
76	.07	.10	.13	.10
152	.09	.09	.10	.09
228	.11	.09	.10	.10
All				.10
		50° Latitude		
76	.09	.07	.09	.08
152	.10	.08	.09	.09
228	.11	.07	.16	.11
All				.09
		52.5° Latitude		
76	.09	.10	.17	.12
152	.08	.11	.11	.10
228	.08	.12	.12	.11
All				.11
		55° Latitude		
76	.08	.12	.12	.11
152	.13	.09	.12	.11
228	.13	.12	.09	.11
All				.11
		57.5° Latitude		
76	.08	.09	.12	.10
152	.08	.11	.11	.10
228	.13	.12	.13	.13
All				.11
		60° Latitude		
76	.17	.11	.12	.13
152	.12	.12	.11	.12
228	.13	.13	.13	.13
All				.13
Average[1]	0.11	0.10	0.11	0.11

[1]By diameter the averages are: 76 mm (0.10); 152 mm (0.10); 228 mm (0.11).

Identification of Trees That Will Have Low Average e/r_1 Ratios—In addition to the significant interaction: elevational class x latitude, the tree-average e/r_1 ratio was significantly (0.05 level) correlated with a few tree characteristics, as follows:

Sign of correlation and tree characteristic	r
Positive	
r_1/r_3 (fig. 9)	0.929
e (fig. 9)	.673
Percentage of compression wood	.336
Age at stump	.148
Elevation, meters	.130
Negative	
Out-of-roundness index (fig. 9)	–0.296
Average ring width at 152-mm-high stump	–.141
Moisture content of complete tree	–.126

In addition to suggesting that low e/r_1 ratios are found in stems with circular cross section and centered pith, low ratios will be found at low elevation in fast-growing young trees with high complete-tree moisture content.

Variation of e/r_1 Within *Latifolia* Trees—The ratio e/r_1 varied significantly with height in *latifolia* trees, the relationship differing with d.b.h. class (fig. 31 and table 6). When this ratio of each of the 2,430 (243 trees x 10 heights) *latifolia* sections was correlated—and each of the 360 *murrayana* sections similarly correleated—with other properties of each section, some significant relationships were evident, as follows:

Section's characteristic correlated with the section's e/r_1 ratio	*Latifolia* (n = 2,430) r	*Murrayana* (n = 360) r
Positive		
r_1/r_2	0.851	0.884
e	.712	.725
Percentage compression wood (fig. 19)	.362	.489
Wood specific gravity	.185	.270
Major diameter	.164	.180
Negative		
Out-of-roundness index (fig. 25)	–0.256	–0.218
Wood moisture content	–.146	–.324
Height above ground, meters	–.141	–.324

Obviously those sections that are cylindrical with centered piths will have small e/r_1 ratios. Additionally, small ratios will tend to be found in high-above-ground sections of large diameter, low specific gravity, and high moisture content; and in sections with low percentage of compression wood (fig. 19).

Murrayana—e/r_1

The mean tree-average ratio e/r_1 for *murrayana* trees was 0.11, with standard deviation of 0.04 and range from 0.05 to 0.18 . The ratio did not vary significantly with either latitude or d.b.h. class.

As noted under the discussion of variation of this ratio within *latifolia* trees (and the tabulation of correlation coefficients), stem sections or short logs sampled from *murrayana* trees will also tend to have low ratios in high-above-ground sections of large diameter, low specific gravity, and high moisture content; and in sections with low percentage of compression wood (figs. 19 and 31).

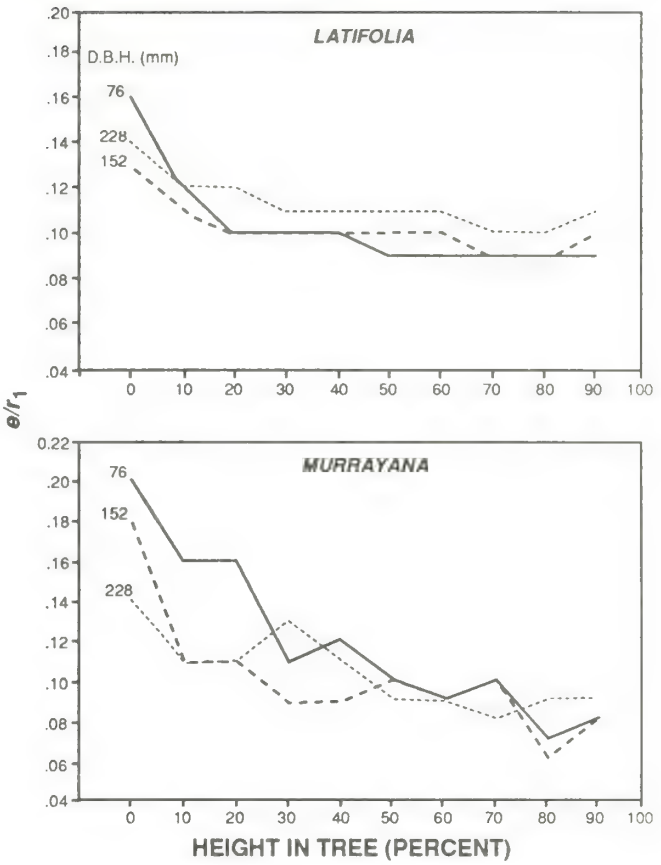


Figure 31—Variation of ratio e/r_1 with height in stems of *latifolia* (81 of each d.b.h.) and *murrayana* (12 of each d.b.h.) trees of three diameters.

e/r_1 of *Latifolia* Compared to *Murrayana*

All latitudes considered, or in the latitudes the two varieties were sampled in common, this ratio did not differ significantly between *murrayana* and *latifolia*. See table 6 and figures 19 and 31 for comparative values.

Latifolia—r_1/r_2

A high value for the ratio r_1/r_2 (fig. 9) indicates a high degree of pith eccentricity; a low value indicates concentricity. The ratio is positively correlated with percentage of compression wood (fig. 19).

Geographic Variation and Variation Among D.b.h. Classes and Elevational Classes—Tree-average values for the ratio r_1/r_2 averaged 1.30 with standard deviation of 0.12 and range from 1.08 to 1.82. These tree-average values differed significantly in a three-way interaction:

Table 13—Tree-average means for *latifolia* of ratio r_1/r_2 related to latitude, d.b.h., and elevational class

D.b.h.	Elevational class: Low	Medium	High	Averages
mm				
		40° Latitude		
76	1.32	1.27	1.19	1.26
152	1.43	1.22	1.32	1.32
228	1.37	1.34	1.34	1.35
All				1.31
		42.5° Latitude		
76	1.29	1.22	1.26	1.26
152	1.36	1.28	1.21	1.28
228	1.19	1.37	1.45	1.34
All				1.29
		45° Latitude		
76	1.38	1.24	1.29	1.30
152	1.29	1.23	1.18	1.23
228	1.19	1.19	1.38	1.25
All				1.26
		47.5° Latitude		
76	1.19	1.30	1.44	1.31
152	1.26	1.22	1.28	1.25
228	1.25	1.19	1.27	1.24
All				1.27
		50° Latitude		
76	1.21	1.18	1.23	1.21
152	1.23	1.21	1.22	1.22
228	1.29	1.15	1.47	1.30
All				1.24
		52.5° Latitude		
76	1.22	1.25	1.57	1.35
152	1.21	1.33	1.29	1.28
228	1.21	1.29	1.33	1.28
All				1.30
		55° Latitude		
76	1.28	1.33	1.36	1.32
152	1.40	1.22	1.35	1.32
228	1.33	1.31	1.20	1.28
All				1.31
		57.5° Latitude		
76	1.29	1.30	1.39	1.33
152	1.18	1.36	1.32	1.29
228	1.30	1.31	1.39	1.33
All				1.31
		60° Latitude		
76	1.58	1.29	1.31	1.39
152	1.32	1.39	1.31	1.34
228	1.36	1.38	1.41	1.38
All				1.37
Average[1]	1.29	1.27	1.32	1.30

[1]By diameter the averages are: 76 mm (1.30); 152 mm (1.28); 228 mm (1.31).

latitude x d.b.h. x elevational class (table 13). Lowest ratios were found in latitudes 45 degrees through 50 degrees, at medium elevation, in trees 152 mm in d.b.h. Maximum ratios were found at 60 degrees latitude. Also trees 228 mm in d.b.h. at latitudes 52.5 degrees and north had high ratios, as did 76-mm trees at low elevation at 40 degrees latitude (table 13). That is, the lowest ratios were at midlatitudinal range, medium elevation, and mid-diameter range, whereas maximum values were at the extremes of latitude, elevational classes, and d.b.h.

Identification of Trees That Will Have Low r_1/r_2 Ratios—In addition to the significant interaction: latitude x d.b.h. x elevational class, the tree-average r_1/r_2 ratio was significantly (0.05 level) correlated with a few tree characteristics, as follows:

Sign of correlation and tree characteristic	*r*
Positive	
Age at 152-mm-high stump top	0.312
Stem taper within live crown, millimeters per meter	.252
Maximum stem crook, inches	.185
Latitude, degrees	.148
Total number of cones on first foot of top 25 branches	.131
Negative	
Average ring width at 152-mm-high stump top	–0.241
Number of live branches	–.181
Average live branch angle	–.158
Length of live crown	–.155
Crown ratio	–.132

These data suggest that low r_1/r_2 ratios will be found in fast-growing young trees with little stem taper in live crowns, little stem crook, few cones on topmost branches, many live branches, long crowns, and large crown ratios.

Variation of Ratio r_1/r_2 Within *Latifolia* Trees—The ratio r_1r_2 varied significantly with height in *latifolia* trees, the relationship differing with d.b.h. class (fig. 32). When this ratio of each of the 2,430 (243 trees x 10 heights) *latifolia* sections was correlated—and each of the 360 *murrayana* sections similarly correlated—with each section's other properties, some significant relationships were evident as follows:

Section's characteristic correlated with the section's r_1/r_2 ratio	*Latifolia* (*n* = 2,430) *r*	*Murrayana* (*n* = 360) *r*
Positive		
e/r_1	0.851	0.884
e	.623	.779
Percentage compression wood (fig. 19)	.378	.518
Wood specific gravity	.197	.312
Major diameter	.120	.189
Negative		
Out-of-roundness index (fig. 25)	–0.274	–0.283
Height above ground, meters	–.168	–.325
Wood moisture content	–.148	–.302

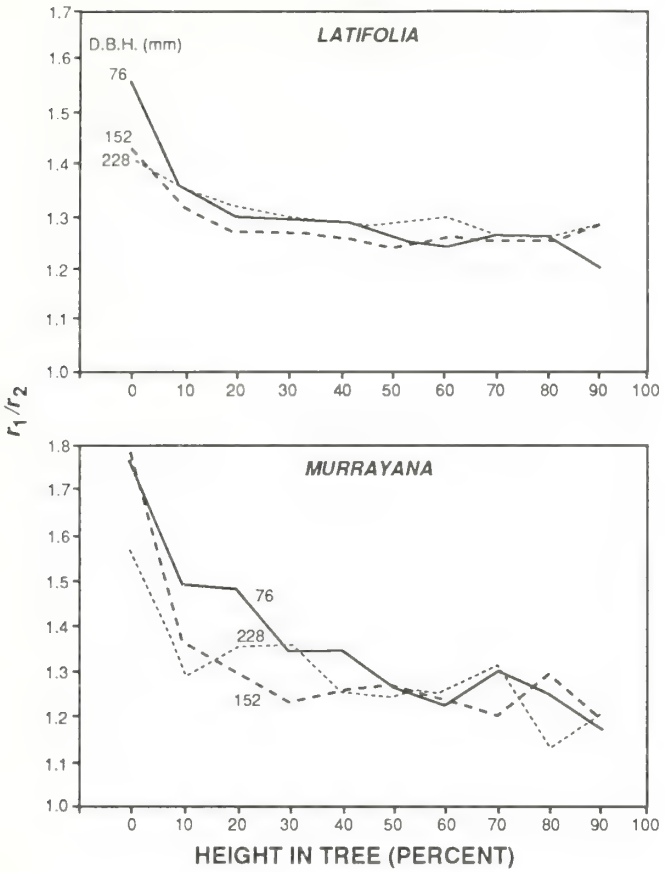


Figure 32—Variation of the ratio r_1/r_2 with height in stems of *latifolia* (81 of each d.b.h.) and *murrayana* (12 of each d.b.h.) trees of three diameters.

Obviously those sections with low values of e and e/r_1 will have low ratios of r_1/r_2. Additionally, small ratios will tend to be found in short logs of small diameter and circular section taken high above ground with little compression wood (fig. 19), low specific gravity, and high moisture content.

Murrayana—r_1/r_2

Variety *murrayana* had tree-average r_1/r_2 ratio of 1.32 with standard deviation of 0.16 and range from 1.12 to 1.64. Values did not differ significantly with latitude or diameter class; there was no significant latitude x diameter interaction. Averages by diameter are summarized as follows:

D.b.h.	*n*	Mean
mm		
76	12	1.36
152	12	1.31
228	12	1.29

With data for all three diameters pooled, tree-average values by latitude were as follows:

Latitude	*n*	Mean
Degrees		
37.5	9	1.35
40	9	1.37
42.5	9	1.33
45	9	1.23

The ratio r_1/r_2 varied significantly with percent height in *murrayana* trees, the relationship differing with d.b.h. class (fig. 32). As noted under the discussion of *latifolia* trees (and tabulation of correlation coefficients), stem sections or short logs sampled from *murrayana* trees will tend to have low ratios of r_1/r_2 if they are of small diameter with circular section, and have little compression wood (fig. 19), low specific gravity, and high moisture content—and are taken high above ground.

r_1/r_2 of *Latifolia* Compared to *Murrayana*

Tree-average ratio r_1/r_2 did not differ significantly between *murrayana* and *latifolia*; see table 6 for comparative values. For varietal differences among individual sections see figures 19, 25, and 32.

CONCLUSIONS

Compression Wood Content

- Compression wood is extremely difficult to detect visually in log ends under woods or mill conditions.

- Stems of virtually all lodgepole pine trees have some compression wood. Of the 243 *latifolia* trees analyzed, only one was free of compression wood. None of the 36 *murrayana* trees examined were free of compression wood. Trees 76 mm in d.b.h. of both varieties had significantly higher stem-average percentage of compression wood than those 152 mm or 228 mm in d.b.h. *Latifolia* trees had less stemwood compression-wood content (5.5 percent) than *murrayana* trees (7.7 percent).

- When evaluating entire stems, highest proportions of compression wood will be found in slow-growing, small-diameter (for example, 76 mm), short trees with little heartwood at stump height, large live-branch angle (branches near horizontal), high stemwood specific gravity, and a relatively high proportion of complete-tree weight represented by the stump-root system and by cones. Lowest stem-average proportions of compression wood will be found in fast-growing, tall trees with long crowns comprised of many branches with small branch angle (and a relatively high proportion of complete-tree weight represented by branches), high sapwood moisture content, much heartwood at stump height, thick stump bark, and a low proportion of complete-tree weight represented by the stump-root system. Stemwood in such trees will have a lower specific gravity than stemwood of trees with a high proportion of compression wood.

- In both *latifolia* and *murrayana* only about one-third of all sections taken at tenth points of tree height have little or no compression wood. Trees 76 mm in d.b.h. had a smaller percentage of sections with little or no compression wood than trees 152 mm or 228 mm in d.b.h. In both varieties, sections sampled at 45 degrees through 50 degrees of latitude had the greatest proportion of sections free of compression wood.

- Of the sections that do have compression wood, nearly three-quarters will display a typical compression-wood pattern (fig. 8, pattern #1) of one-sided eccentricity in which the main body of compression wood is opposite an eccentrically located pith, and along a line projected from pith through the center of the largest circle that can be inscribed within the section (fig. 9B).

- In both *latifolia* and *murrayana* incidence of compression-wood pattern #1 dominates near ground level (fig. 14), but incidence of this pattern diminishes with height in tree. Sections free of compression wood are infrequent in the lower stem; upper stem sections are more frequently free of compression wood.

- Sections or short logs sampled from stems of both varieties will tend to have high percentages of compression wood if they are out of round and close to ground level, and have eccentric piths, high specific gravities, and low moisture contents (figs. 19, 20, and 21). Also, there is a weak tendency for small-diameter wood to have more percentage compression wood than large-diameter wood.

- One of the better indicators of compression-wood content in stem sections or short logs (fig. 19) is the ratio e/r_1 (defined in fig. 9). This ratio will be smallest (and compression wood content low) if sections are cylindrical with centered piths; small ratios will also tend to be found in high-above-ground sections of large diameter, low specific gravity, and high moisture content.

- The ratio r_1/r_2 (defined in fig. 9) is also one of the better indicators of compression wood content (fig. 19).

Stemwood Out-of-Roundness

- Tree-average out-of-roundness index (fig. 9) averages 0.91 and does not differ significantly between varieties or with tree d.b.h. or elevational zone. It does vary with latitude, however; tree stems are most nearly circular in average cross section in those latitudinal zones from 40 degrees to 55 degrees (with the exception of zones at 47.5 degrees and 52.5 degrees), and are more elliptical in the northernmost zones of 57.5 and 60 degrees.

- In addition to latitudinal differences, entire stems are most likely to average most circular in cross section in fast-growing trees of high moisture content, low specific gravity, with pith not eccentric, little stem crook, low bark percentage of complete-tree ovendry weight, and with many small branches making a small angle with the stem above them. Because latitude is inversely correlated with the elevation at which *latifolia* grows, trees at higher elevations may have stems more nearly circular in cross section than those at lowest elevation.

- Stemwood of both varieties is most nearly circular in cross section near midheight (fig. 24).

- Sections or short logs of stemwood of both varieties will tend to be out of round if they contain much compression wood, have eccentric piths, high specific gravity, small minor diameter, and low moisture content; the last two relationships, although statistically significant, are weak.

Minor Stemwood Diameter

- In trees of comparable d.b.h. (within the range of this study), and at comparable percentages of tree height, *murrayana* stems have slightly smaller minor diameters (defined in fig. 9A) than *latifolia* stems (fig. 27).

Pith Eccentricity, *e*

- Tree-average pith eccentricity, *e* (defined in fig. 9), averages about 6.7 mm and does not differ between varieties. Small-diameter trees have significantly less pith eccentricity than large trees (fig. 28), and trees average least eccentricity if growing in the midelevational zone. Pith eccentricity in *latifolia* is smallest (5.5-6.3 mm) in the intermediate latitudinal zone from 45 to 52.5 degrees, and is larger in more southerly and more northerly latitudes (6.8-8.0 mm).

- Tree-average pith eccentricity is least in slow-growing, small-diameter, short trees with circular stem sections, and heartwood and stembark of high moisture content—but sapwood of low moisture content.

- Individual sections or short logs will have least pith eccentricity if they are small in diameter, near circular in cross section, and in the upper stem (figs. 28 and 29), and if they have little compression wood, low specific gravity, and high moisture content (figs. 29 and 30).

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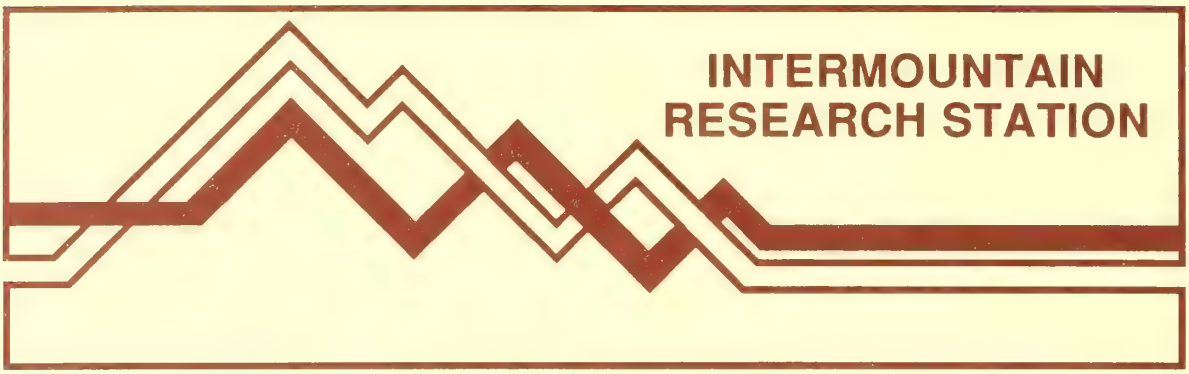
Trees 76 mm d.b.h. had higher stem-average percentage of compression wood than those 152 mm or 228 mm d.b.h. *Latifolia* had less compression wood (5.5 percent) than *murrayana* (7.7 percent). In both varieties, stem sections from 45° through 50° latitude were proportionally more free of compression wood than sections from other latitudes. Transverse stem sections typically displayed a main body of compression wood opposite an eccentrically located pith. Percentage of compression wood tended to be higher in stems that were out of round and close to ground level, and if pith was eccentric, specific gravity high, and moisture content low. Cross sections averaged most elliptical in trees from 57.5° and 60° latitude. Both varieties were most nearly circular in cross section near midheight. Pith eccentricity averaged 6.7 mm and was least in intermediate latitudes (45° through 52.5°).

KEYWORDS: wood technology, forest products, pith eccentricity, stem form, geographic variation, *Pinus contorta* var. *latifolia*, *Pinus contorta* var. *murrayana*



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Combustion Recovery of Flaming Pine Needle Fuel Beds Sprayed With Water/MAP Mixtures

Aylmer D. Blakely

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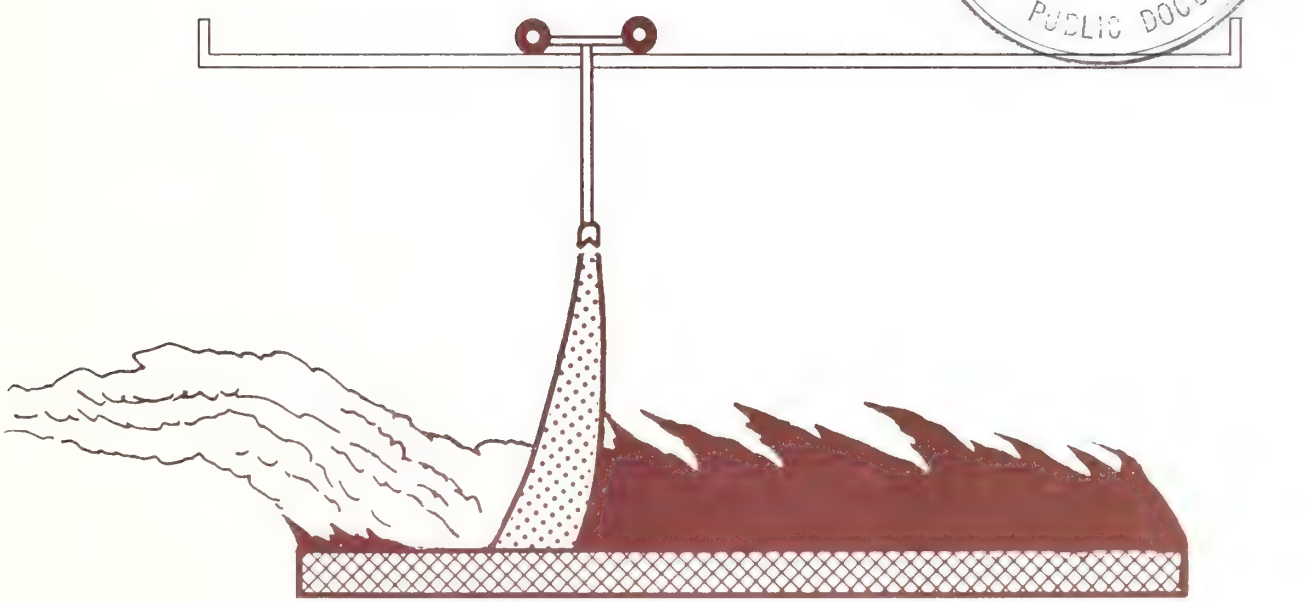

RESEARCH SUMMARY

The purpose of this study was to quantify the fire extinguishing capabilities of water with small amounts of mono-ammonium phosphate (MAP) added. Replicate fires were conducted to quantify the differences in energy release rates and durations before, during, and after treatments. In a wind tunnel with controlled environment 5 mi/h wind, 90 °F, 20 percent R.H.), ponderosa pine needle fuel beds were ignited, allowed to reach maximum energy release rate near 300 Btu/s, and five different amounts of water and water plus MAP were sprayed into the flaming beds. The consequent smoldering fuel beds were monitored for weight loss as the flaming combustion recurred, burned most of the available fuel, and then died out.

Weight loss traces were divided into segments and analyzed separately for reactions to different water and MAP applications. The segments were identified as BC, the "fire knockdown" capbility of the application; SS1, the "holddown" capability; and SS2, the magnitude of the energy released and the time elapsed during maximum combustion recovery. Major differences in reactions to the different treatments were found between trace segments of individual fires, and these correlated well with reactions shown by the weight changes in trace segments of replicate fires.

Combustion recovery data from these fires show that water alone is the principal agent reducing flaming combustion to smoldering and that the chemical adds slightly to the reduction. Water reduced the energy release rates to which the fires recovered, but water plus chemical reduced the levels significantly more. The same was true for extending the time that the combustion stayed at the reduced energy release rates. The data in this study show a significant advantage in adding chemical retardant to water. The capability of water to immediately reduce flames to smoldering combustion was enhanced only slightly by retardant chemicals. But the chemical significantly reduced fire intensity and extended the times that flames were reduced as the smoldering continued beneath the surface of the burning fuel. Chemical retardant added to water can be a definite advantage during vegetation fire suppression efforts.

THE AUTHOR

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Combustion Recovery of Flaming Pine Needle Fuel Beds Sprayed With Water/MAP Mixtures

Aylmer D. Blakely

INTRODUCTION

Forest fire retardants may be applied to wildfires from either air or ground tankers, but the majority of the approximately 30 million gallons (the volume varies by severity of the fire season) used each year is applied from airtankers. Less than 1 percent is applied by groundtankers. A Washington Office Policy Analysis Staff Report (Gale 1983) estimates that 30 percent of retardant delivered by airtankers is in direct attack to totally extinguish flaming combustion and stop the fire's advance. (This estimate may be low if the commonly used "half-on, half-off" tactic were included.) Two other reasons for using retardant are to cool the fire so firefighters or equipment can work closer to the fire and to slow the fire's advance until some other action can be taken. Indirect attack—placing retardant away from the active firefront—may be used if the fire is too intense and/or the terrain or fuels are not particularly conducive to direct attack.

Most currently approved retardants are long-term slurries that contain chemicals that are still effective even after the water has evaporated. Therefore, most retardant-effectiveness studies have been conducted with water/chemical mixtures that were sprayed onto fuels then allowed to dry before being ignited. Few studies have been made to quantify the fire-extinguishing abilities of currently used long-term fire retardant formulations that contain phosphates and sulfates of ammonia or other chemicals that inhibit combustion by altering fuel pyrolysis. No comprehensive laboratory studies under controlled conditions have been made to study the fire-extinguishing capabilities of thickened or unthickened water on mat-type fuel beds. Some studies have been made in uncontrolled conditions and others used overhead sprinklers to apply different retardants to lumber or boxes (Truax 1939; Grove and others 1962).

Long-term Versus Short-term Retardants

Most fire specialists have long believed that long-term fire retardants are the most cost effective because the airtanker cost is the major part of the total delivery cost. But today costs per load of long-term retardant may approach the cost for airtanker delivery. It has therefore been suggested that costs can be reduced by delivering a cheaper retardant. The question arises, is a less expensive retardant cost effective? Can the cheaper retardant in forms such as plain water, thickened water, or foam, retard fire and still significantly aid the firefighter, in some, if not all, situations. Use of the cheaper retardant in lower fire-intensity situations can save money. For example, suppose the difference in cost of long-term and short-term retardant were 35 cents per gallon. During a fire season when 30 million gallons were used, using the short-term retardant only 10 percent of the time would save more than $1 million.

Some of the tradeoffs between short-term and long-term retardants are: (1) Acceptability—long-term chemical retardants may be unacceptable for use in municipal water sheds. (2) Color—persistent iron oxide pigments in some retardants are unacceptable in wilderness and residential areas. If not washed off immediately, fire retardant salts or pigments can ruin car paint and stain homes or scenic rock formations. (3) Effectiveness—what are the limits of effectiveness for various retardants under different fire/fuel situations, especially when the fire is under control (during mop-up or low fire-spread situations) or when the fire intensity is so high that retardant obviously will not be effective. (4) Application—if long-term retardants are to be used often in direct attack fire-extinguishing capabilities of new and different retardant formulations must be quantified. A more precise method is needed than just spraying retardant onto a burning pile of brush under ambient conditions and calculating how much retardant it takes to stop the flaming and smoldering, with no measurement of the amount of "overkill."

Long-term Versus Short-term as Extinguishers

The purpose of the study reported here was to quantify the fire-extinguishing capabilities of water containing mono-ammonium phosphate (MAP), a commonly used chemical in forest fire retardants. The study method realistically tests actual retardant use because retardants usually retard combustion and seldom totally extinguish it, especially during the initial application. Ideally, a retardant would completely extinguish all flaming and glowing combustion. But many times the fire is only retarded or slowed, or fire intensity is decreased for only a short time. Knowing the effects of different amounts of water and chemicals in different fire and fuel situations is important in fire suppression efforts. Even though the fire's intensity level is decreased for only short periods, those times can be used by firefighters to get closer to the fire for more effective direct attack.

We need to answer questions like the following ones. Does water with chemicals knock down flame better than water alone? Which application causes the energy release rate to be reduced for the longest time? On what fuels and fire intensities can the water or chemicals do the required job (be effective)—not necessarily extinguish, but lower the fireline intensity for a period during which some other fire-stopping action can take place? This goes along with the idea of "retardant." Can water (short-term retardant) be substituted for water plus retardant (long-term retardant) with satisfactory results? If so, in what situations? Is there a significant advantage to using long-term retardant formulations to *extinguish* fire, and is it cost effective compared to water alone or with thickeners added?

Plain water is commonly used to extinguish fire because it is readily available, and it can be effective in the right circumstances. When water is plentiful and readily available, chemicals are seldom added except in some special situations such as aircraft fires where water alone has limited effectiveness. In situations where water is scarce and must be used judiciously, such as aircraft delivery on wildfires, additives are commonly used to increase effectiveness. Fire extinguishers containing only dry chemicals are commonly used for structural and other "inside" fires with high success unless the volume of the extinguisher is too small for the quantity of burning material. The extinguisher usually contains chemicals that smother burning materials and/or decrease the flammability of evolved gases rather than just absorbing heat energy. Ironically, few if any common extinguishers contain only water.

The least use of additives seems to be in water dispursed from ground tankers. The reasons are often: (1) the lack of specialized equipment to mix and pump water plus additives; (2) the adverse effects of the chemical residue on salvageable items remaining after the fire; (3) the logistics of applying water plus additives; and (4) the cost (Pickett 1975). Of these reasons, the lack of proper equipment is the most important deterrent to use of additives. Often the advantages in reducing fire intensity are overlooked, and firefighters have not been properly trained or are unaware of the advantages of water additives.

How Fire Is Extinguished

Water extinguishes fire as follows: (1) by reducing the oxygen supply; (2) by cooling to temperatures below that required to ignite unburned fuel particles and sustain combustion; (3) by diluting flammable gases to a concentration at which they will not ignite; (4) by chemically altering pyrolysis of rapidly heating fuels enough to change the composition and flammability of evolved gases and vapors; and (5) combinations of all of the above actions. When water is applied to burning forest fuels, a combination of all of these actions occurs. We generally think of cooling and smothering as the most effective. But what happens when water is applied in too small a quantity or in a form that limits its availability to alter combustion? For example, when a straight stream of water is sprayed into the flames, the water contacts the fuels in a small area. That area may be extinguished while the water is being directed at it. But when the water stream is removed, the surrounding flames quickly evaporate the water and the area will flame again unless all the adjacent fuels have also been cooled enough to prevent heat transfer or there is chemical present to retard combustion.

In wildland fires the main purpose of water is to cool the combustion to a point that the fire will not sustain itself. On indoor structures an important method of extinguishment is to fill a room with the right amount of water in a spray form so that the room is filled with steam that both cools and smothers the flames and dilutes the flammable gases and vapors (Royer 1952). The same principle can be used for open wildland fires, but not nearly as effectively, because the steam cannot be confined in an effective volume. Therefore we find that water is effective in a straight stream form, but is not as effective as a mist or steam would be for cooling, smothering, and diluting.

Previous Retardant Testing

Many tests have been performed to determine the advantages of adding chemicals to water for extinguishing fires. In the late 1930's Truax (1939) showed that several chemicals would improve the effectiveness of water to stop flaming and glowing combustion on burning fires in beds of leaves and needles. Truax showed that the added chemicals helped to prevent rekindling, but he concluded that if plenty of water was available the addition of chemicals did not improve the effectiveness of water enough to warrant the additional logistical effort and expense. A USDA Forest Service report (1955) showed that energy release was decreased when water solutions of ammonium sulfate and ammonium phosphate were applied to burning piles of brush. Studies done with additives (Groves 1962) showed that they could increase the extinguishing effect of water. Thickeners, foams, retardant chemicals, surfactants, and reflectors all increased the effectiveness of water. But evidently the increased effectiveness of additives shown by these studies did not convince firefighters that the advantages would surpass the disadvantages caused by extra needed equipment and logistics when using additives in ground engines and pumpers. Therefore, the use of additives has not become prevalent among wildland or structural engine crews. Recently, much interest has been shown in the use of small amounts of chemicals that can be added to water to produce different qualities of foam for different firefighting situations. These foams are designed to cool and smother flames, and they require a minimum of extra equipment and effort to apply.

Blakely (1985) introduced a laboratory method for quantifying the fire-extinguishing capabilities of water alone and water with added thickeners and chemical fire retardants. The objective of the study was to develop a method for quantifying differences between the fire extinguishing capabilities of water with and without fire retardant chemicals, and with or without thickening agents. The study identified water as the principal cooling agent for knocking down (KD) flaming combustion. Adding retardant chemicals improved the flame KD capabilities of water very little, but the increased viscosity and added retardant salt did minimize the measured fire intensities. The report discussed only eight fires that were conducted

to demonstrate the feasibility of using the new method for evaluating and studying the extinguishment capabilities of fire retardants.

METHODS

The previous study by Blakely (1985) used "combustion recovery" to examine the effects of water alone and water combined with thickening agents and/or fire retarding chemicals on flaming and smoldering combustion. The concept of combustion recovery examines the consequences when retardant quantity is insufficient to knock down the flames and absorb all the energy being released by the burning fuel. Smoldering continues in the untreated fuels beneath the treated fuels. The heat from below evaporates the water and rapid combustion (flaming) starts again. The time required for flaming to recur and the level of energy release depend on the water and chemicals that are protecting the fuel from the heat source beneath the upper layers.

Fuel is less available to burn when coated with water or chemicals that prevent heat absorption or the coating causes fuel to burn at an intensity too low to ignite the adjacent fuel elements. Theoretically, if the retardant or water protects a fuel element and does not allow ignition before the contributing heat source has burned itself out, or if the energy release rate (E_R) is too low to transfer ignition energy to the next element, then the fire will not sustain itself. In most cases it is not a single fuel element that contributes to ignition but rather the total heat energy that each element receives from the entire mass that is burning.

For this study, beds made of 4 pounds of untreated ponderosa pine needles were surface ignited along the edges and middle and allowed to become fully involved and reach maximum E_R before treatment was started. (Irradiance proportional to E_R was measured with a Gier-Dunkel radiometer.) The fire intensity of untreated fuel increased to maximum output in about 20 seconds, when the treatment was started. The retardant was sprayed in a fan-shaped pattern directly into the flames from an overhead nozzle that was moved upwind along the bed at a speed set by the predetermined amount of treatment. Different amounts of retardant were applied to replicate fires with similar pretreatment burning rates. After application, beds were allowed to burn down to a minimum E_R and then allowed to recover to a maximum, subject to the fuel quantity remaining and the effectiveness of the treatment. During the burn, weight loss and radiation energy emitted from the fuel bed and flame plume were recorded on a micro computer and monitored for about 12 minutes after the end of retardant application. Weight loss and irradiation traces and weight/time data taken from the traces are listed in the appendixes. The experimental burns were conducted in a controlled-environment wind tunnel in a 5 mi/h wind at 90 °F free air temperature and 20 percent relative humidity.

During the 1985 study, insufficient data were gathered to present a statistical analysis of the various effects. The study reported here included several more experimental burns that are used in an analysis that shows correlations of retardant amounts to reductions in energy release rates and durations. The previous study showed that thickening agents, retardant chemical concentrations, and total amounts of water had measurable effects on the energy release rates. This study does not examine the effects of thickening agents but only the effects of water alone and water combined with mono-ammonium phosphate (MAP).

Five different amounts of water were applied to burning fuels: 144, 216, 288, 360, and 432 g. There were four replicates of the 144-g application and three replicates of each of the others. In addition, two replicates each of 144, 288, and 432 g water with 24 g mono-ammonium phosphate added were applied to burning needles. The solution percentages (on a weight/weight basis) were 14.3, 7.7, and 5.3, respectively. The amount of MAP was held constant to examine the effect of equal amounts of chemical distributed into the fuel bed by different amounts of water. Volumes of liquid converted to gallons per 100 square feet (gpc) are: 144 g = 0.32 gpc; 288 g = 0.64 gpc; and 432 g = 0.95 gpc.

Experimental Methods for Measuring Combustion Recovery E_R

The methods used in this study are similar to those used in the Blakely (1985) study but with some improvements in data acquisition and recording equipment and data analysis techniques. The system for measuring weight loss was changed to a more accurate balance, with greater sensitivity to rapid weight changes. The same radiometer was used, but it was positioned to view all of the combustion zone and record the irradiation so that it could be used to more precisely detect changes in the fuel bed weight loss. In the previous study, the radiometer trace was used only for determining the point of maximum E_R when the sprayer was turned on.

The weight loss traces were analyzed electronically and with computer software to convert to Btu's and Btu/s. (Previous laboratory studies [George and Blakely 1970] have shown that ponderosa pine needles have a heat of combustion of 8,745 Btu/lb). The computer program calculated the E_R by averaging fuel bed weights along segments of the traces that showed constant weight loss (steady state or SS). Trace segments were determined by examining the irradiation trace for high and low E_R points (described below). These points were designated where major changes occurred in the fire intensity. The time points were picked from the irradiation trace rather than from the weight trace because the changes were more obvious and easier to locate on the irradiation trace.

The maximum pretreatment E_R (Btu/s) for each fire (occurring soon after ignition) was compared to E_R that occurred as the fire recovered from the different treatments. For each of the weight loss segments described below, a reduction percentage was calculated. The percentages were used for comparisons rather than just Btu/s because of slight differences in the pretreatment E_R for each test fire. The length of time (duration) each fire burned at the different posttreatment steady state E_R was measured and used as another parameter for determining effectiveness. Each set of data was fitted by a least squares method; the plotted data and equations are in the appendixes.

Combustion Recovery Phases of Fires

Trace Segment B to C—The energy release recorded immediately after sprayer shutoff is the segment of the weight loss trace from B to C (fig. 1). This segment describes the E_R that is affected by both the water and the chemical. It is the segment that best indicates the fire "knock-down" (KD) abilities of the retardant. The duration of B to C is short (usually less than 15 seconds) compared to the other steady-state E_R segments; therefore the average E_R was measured for only a few seconds immediately after treatment shutoff.

The KD parameter, not used in the 1985 study, was detected in the current study, when the radiometer was repositioned and more sensitive weight loss equipment was used. KD was first noticed as glowing combustion at the upwind end of the burning fuel bed. Under close examination, a steep segment was found on the weight loss trace and a corresponding rapid increase on the irradiation trace for a short period that quickly decreased and became the first steady-state burn trace (SS1). The KD parameter was first considered to be part of the SS1 energy release, but when examined separately its E_R was found to be sensitive to amount and type of treatment that was being applied to the burning fuel.

First Steady-State Segment (SS1)—Immediately after treatment shutoff and KD, the weight loss rate decreased slightly and began an extended steady state (SS1). SS1 was a period when the maximum amount of retardant was on the fuel and the energy release was at

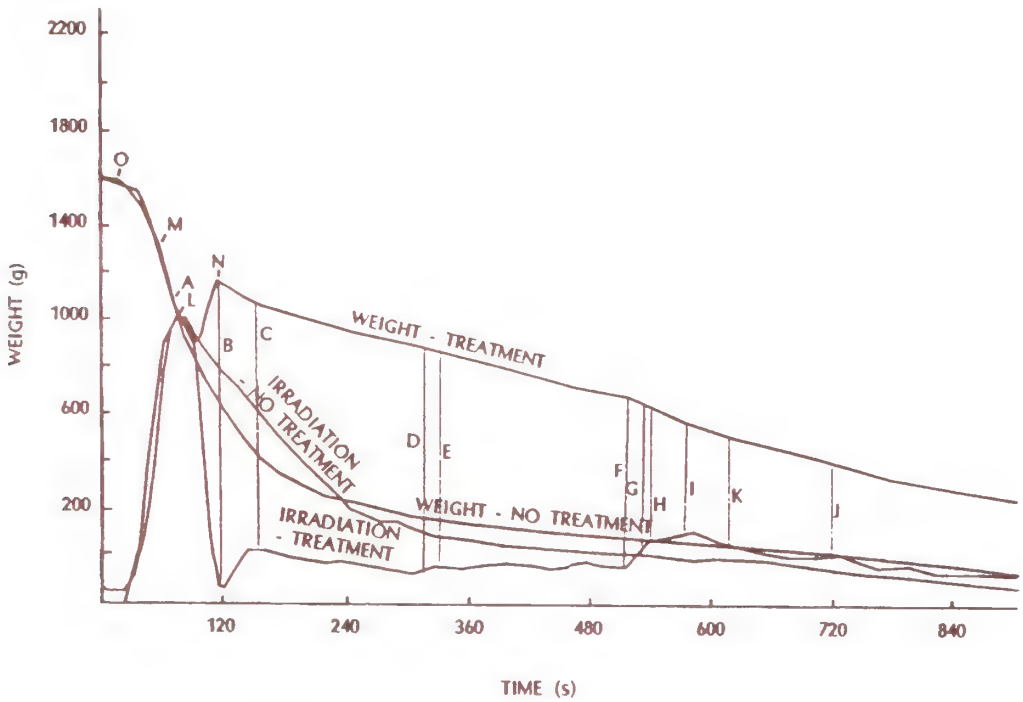

Figure 1—Points on the weight loss and irradiation curves that correspond to major changes in energy release rate caused by application of retardant, evaporation of water, and effects of chemical application. Displays traces for a 432-g application of water plus MAP.

A-K: times taken from irradiation trace
L-O: times and weight traces taken from weight trace
A: maximum energy release
B: lowest E_R on irradiation trace immediately after treatment
C: beginning of fire effects after retardant application and start of SS1
D: minimum E_R during SS1
E: short E_R increase during SS1
F: low energy output point where fire starts to recover to maximum E_R—corresponds to start of SS2
G: E_R is back to same level as at start of SS1
H: SS2 E_R begins to fall
I: combustion recovery reaches it's maximum
J: end of SS2—E_R begins steady decrease until fire is out
K: E_R recovers to same level as at the start of SS1
L: time when the treatment starts
M: point 10 seconds before treatment starts—used for calculating maximum energy release before treatment
N: time when treatment stops
O: weight of fuel bed before ignition

a minimum. During this period, most of the water was being driven off so duration was directly related to the amount of water applied. The flaming combustion had been knocked down so that there was only smoldering combustion beneath the surface. The smoldering combustion produced sufficient heat to continue drying the treated fuels and sustain itself until enough heat was generated for flames to reappear. At that point, the total energy release of the fuel bed began to accelerate and recover (SS2).

The first steady-state period was followed by a second steady-state period (SS2) that reached a higher weight loss rate with increased flaming. The two steady-state periods varied in E_R and duration, corresponding to the total amount of water and other chemicals applied. The effectiveness of the retardant applications was determined by comparing the magnitude and duration of weight loss rates.

Second Steady-State Segment(SS2)—SS2 started as SS1 ended, but the E_R calculation was started after the weight loss rate became constant. By the time SS2 started, most of the water had evaporated, and some of the retardant chemical still remained on the fuel. During SS2 the E_R reached its highest magnitude since the retardant was applied, but the intensity never equaled the pretreatment rate because during SS1 most of the upper fuel layers burned away and the total fuel loading was reduced.

E_R Duration Measurement—Elapsed time (duration) was measured so fire's reactions to water and/or chemical could be determined and compared. Duration was the time E_R stayed at a level that sustained combustion under the existing conditions. When retardant was on the fuels, the E_R was at a steady state much below the pretreatment E_R. Duration was a function of E_R. When the treated fuel was burning, it was the treatment that controlled the duration by limiting the available fuel and thereby controlling the E_R.

RESULTS AND DISCUSSION

During untreated control burns, the burning rate of fuel accelerated rapidly to a maximum, held there momentarily, then decreased at a much slower rate until the combustion stopped (fig. 1). For extinguishment tests, when the irradiation trace reached its highest point, water or water plus MAP was applied to the flames of burning fuel beds. None of the applications completely stopped combustion; therefore sufficient heat remained to allow combustion recovery. The extent of recovery depended on the amount of water and/or chemical present on the fuel that could retard the combustion by heat absorption, cooling, alteration of flammable products, and so on.

Weight Loss Trace Segments BC, SS1, and SS2

Several different methods were used to describe what happened when water with or without chemicals was sprayed into the flaming fuel bed. The weight loss and irradiation traces were analyzed to define the time points and trace segments when burning rates changed. E_R was determined from the different segments of weight loss traces then plotted in Btu/s or as a fraction of the maximum untreated fuel E_R. The segment duration times were plotted in minutes or as a fraction of duration of other trace segments.

Several trace segments identify the fire's reaction to retardant, but the most useful line segments are B to C, C to F (the first steady state [SS1]), and F to J (the second steady state [SS2]). B to C is a measure of the flame knockdown (KD) capability of the retardant; SS1 is a measure of the holddown capabilities of the retardant; and SS2 shows the level of the fire intensity as the fire recovers to the maximum attainable with the remaining fuel, water, and/or retardant chemical still present. SS2 E_R is a sustained level for several seconds or minutes. The E_R at I, the point when the maximum combustion recovery occurred, was calculated by averaging the weight loss for 3 seconds on each side of I. The time for the fire to recover to that level was measured between point B and I (BI).

BC Energy Release Rate—The rate of weight loss for 10 seconds immediately after the application stopped (segment B to C) determined the E_R that occurred as retardant was sprayed into the flames and fuel. This E_R was much lower than the pretreatment burning rate and higher than the SS1 rate. It lasted for only the few seconds before the E_R subsided to a steady state. Figure 2 and table 1 show the relation of amount of water applied to the fuel bed vs. the reduction in E_R shown as a percentage of the pretreatment E_R immediately before retardant application. The E_R was reduced as expected with each increase in the amount of water applied. The addition of MAP caused an additional reduction in E_R of from 6.8 to 7.2 percent, with the highest reduction at the lowest chemical concentration and the most water applied. Figure 2 shows that spraying 144 g water to the burning fuel bed reduced the E_R by 69.5 percent. When 24 g MAP was added to the 144 g water (14.3 percent solution) and applied to the burning beds, the E_R was reduced another 6.8 percent over plain water. Three times as much water reduced E_R by 80.9 percent and adding MAP reduced the E_R another 7.2 percent.

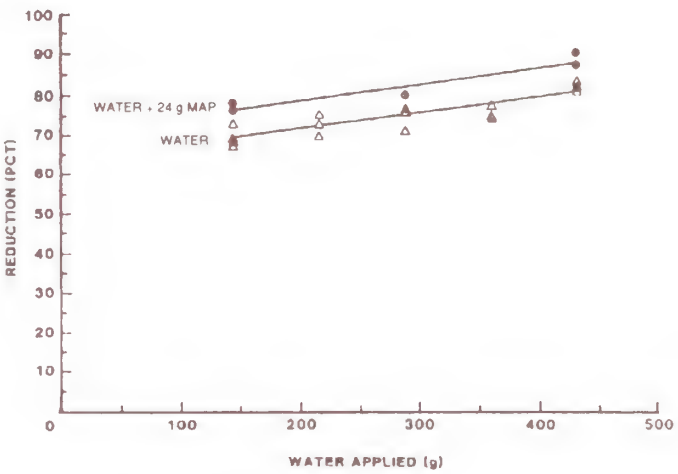

Figure 2—BC (knockdown)—reduction of energy release rate for water, and for water plus MAP.

Table 1—BC energy release rate data

Fire	Water	MAP	BC	BC reduction	Pretreatment E_R
	- - - - g - - - -		Btu/s	Percent	Btu/s
M28N1	144	0	72.3	72.9	267
M28N2	144	0	86.7	67.6	268
M28N3	144	0	75.2	69.4	246
M28N4	144	0	86.7	68.7	277
JUN11N2	144	24	55.9	77.6	249
JUN11N3	144	24	54.0	76.4	229
JUN8N1	216	0	77.1	72.7	282
JUN8N2	216	0	61.7	75.1	248
JUN8N3	216	0	73.2	69.8	242
JUN9N1	288	0	71.3	71.3	248
JUN9N2	288	0	61.7	76.5	262
JUN9N3	288	0	55.9	75.9	232
JUN11N4	288	24	46.3	80.1	233
JUN11N5	288	24	46.3	80.2	234
JUN9N4	360	0	55.9	74.6	220
JUN9N5	360	0	55.9	77.7	251
JUN9N6	360	0	61.0	75.4	248
JUN4N1	432	0	44.3	83.5	269
JUN4N2A	432	0	42.4	82.5	242
JUN10N1	432	0	48.2	81.3	258
JUN11N6	432	24	25.1	90.7	271
JUN11N7	432	24	30.8	87.4	245

Table 2—SS1 energy release rate data

Fire	Water	MAP	SS1	SS1 duration	SS1 start	SS1 reduction
	- - - - g - - - -		Btu/s	- - - - min - - - -		Percent
M28N1	144	0	52.5	0.30	0.12	80.3
M28N2	144	0	62.4	.63	.17	76.7
M28N3	144	0	60.2	.53	.47	75.5
M28N4	144	0	60.6	.70	.10	78.1
JUN11N2	144	24	13.7	2.13	.90	94.5
JUN11N3	144	24	25.1	2.47	.32	89.0
JUN8N1	216	0	29.6	1.83	.50	89.5
JUN8N2	216	0	24.3	1.60	.43	90.2
JUN8N3	216	0	24.0	1.50	.58	90.1
JUN9N1	288	0	25.6	1.93	.77	89.7
JUN9N2	288	0	33.0	1.60	.63	87.4
JUN9N3	288	0	22.7	2.60	.68	90.2
JUN11N4	288	24	22.9	5.00	.72	90.2
JUN11N5	288	24	16.4	4.67	.95	93.0
JUN9N4	360	0	23.8	3.33	.90	89.2
JUN9N5	360	0	25.8	5.33	.75	89.7
JUN9N6	360	0	28.6	5.53	.58	88.5
JUN4N1	432	0	17.7	5.13	.98	93.4
JUN4N2A	432	0	21.5	5.93	.63	91.1
JUN10N1	432	0	21.6	4.27	.67	91.6
JUN11N6	432	24	12.5	8.50	3.68	95.4
JUN11N7	432	24	14.8	7.40	2.95	94.0

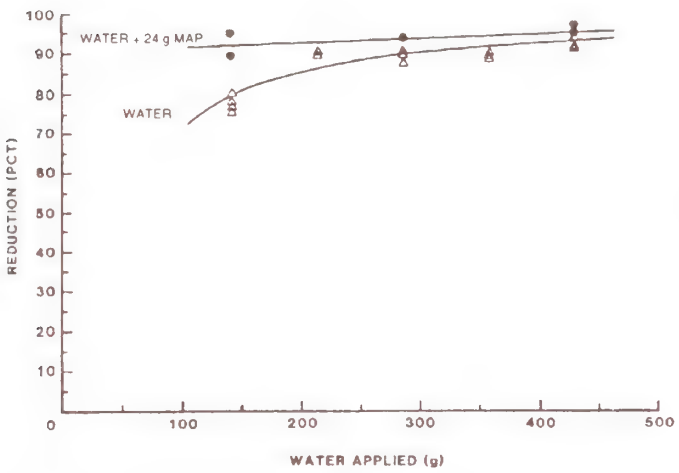

Figure 3—SS1 (holddown)—reduction in energy release rate for water, and for water plus MAP.

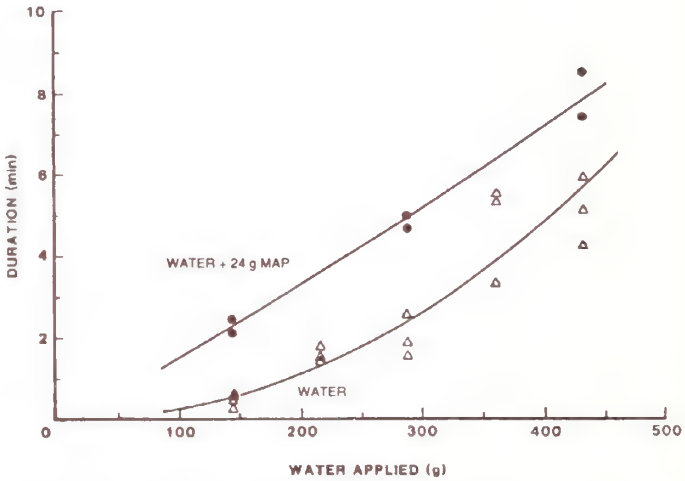

Figure 4—SS1 (duration of holddown) for water, and for water plus MAP.

SS1 Energy Release Rate—Data for SS1 are shown in table 2 and figure 3, and also in appendix C. By spraying 144 g water, the pretreatment E_R was reduced by 79.1 percent. By adding 24 g of MAP to 144 g water, the E_R was reduced by 91.4 percent, slightly more than the reduction caused by doubling the water (288 g) with no chemical. Clearly, the first 144 g of water had the most effect; each additional 72 g added to the effect but by a much reduced amount. Tripling the water reduced the E_R 92.4 percent and adding 24 g MAP to the water reduced E_R only another 1.7 percent.

Figure 4 shows the effects of water alone and water with MAP on the duration of SS1. When 144 g water is applied, the SS1 E_R is held to a minimum for 0.56 minutes before it starts to recover and flame again. By adding 24 g MAP to the water, the holddown time is extended almost fourfold as long as water alone. Doubling the water treatment to 288 g increases the holddown period fivefold the duration with 144 g treatment, and tripling the water increases the duration tenfold. Adding 24 g MAP to 432 g water extended the duration of the SS1 E_R to just under $1^1/2$-fold.

Table 3—SS2 energy release rate data

Fire	Water	MAP	SS2	SS2 duration	SS2 start	SS2 reduction
	- - - - g - - - -		Btu/s	- - - - min - - - -		Percent
M28N1	144	0	96.4	0.70	0.82	63.9
M28N2	144	0	96.9	.60	.90	63.8
M28N3	144	0	82.8	1.07	1.07	66.3
M28N4	144	0	90.2	0.93	1.07	67.4
JUN11N2	144	24	47.7	1.33	3.77	80.8
JUN11N3	144	24	36.6	3.40	3.08	84.0
JUN8N1	216	0	66.1	1.43	2.95	76.6
JUN8N2	216	0	69.2	1.67	2.92	72.1
JUN8N3	216	0	54.6	1.50	2.50	77.4
JUN9N1	288	0	44.5	1.30	4.17	82.1
JUN9N2	288	0	46.2	1.60	2.35	82.4
JUN9N3	288	0	49.5	1.67	4.90	78.7
JUN11N4	288	24	21.4	3.83	6.00	90.8
JUN11N5	288	24	28.2	2.27	6.53	87.9
JUN9N4	360	0	32.2	3.03	4.65	85.4
JUN9N5	360	0	80.4	.87	7.15	68.0
JUN9N6	360	0	55.3	1.67	6.57	77.7
JUN4N1	432	0	26.1	5.10	7.40	90.3
JUN4N2A	432	0	25.6	3.47	6.90	89.4
JUN10N1	432	0	38.9	3.57	5.33	84.9
JUN11N6	432	24	14.2	3.33	12.18	94.8
JUN11N7	432	24	16.1	5.00	10.42	93.4

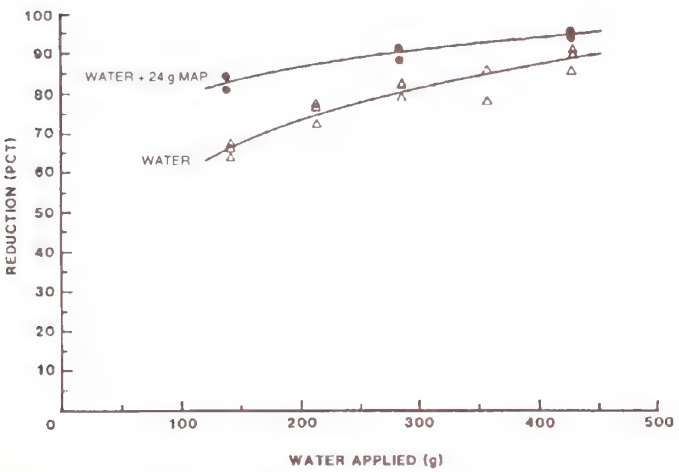

Figure 5—SS2 (combustion recovery)—reduction in energy release rate for water, and for water plus MAP.

SS2 Energy Release Rate—SS2 energy release data for individual fires are shown in table 3 and figure 5, and also in appendix C. The SS1 E_R (144-g water application) increased by 16.4 percent after 0.56 minutes, the beginning of SS2 E_R, and continued at that rate for 0.92 minutes before slowly decreasing in intensity until all combustion stopped. Adding 24 g MAP to 144 g water reduced the SS2 E_R 82.3 percent. Doubling the water (without MAP) reduced the SS2 E_R by 79.8 percent; adding 24 g MAP to the water reduced E_R an additional 9.8 percent. Tripling the water (432 g) reduced the E_R by 87.9 percent and adding 24 g MAP reduced E_R another 6.0 percent.

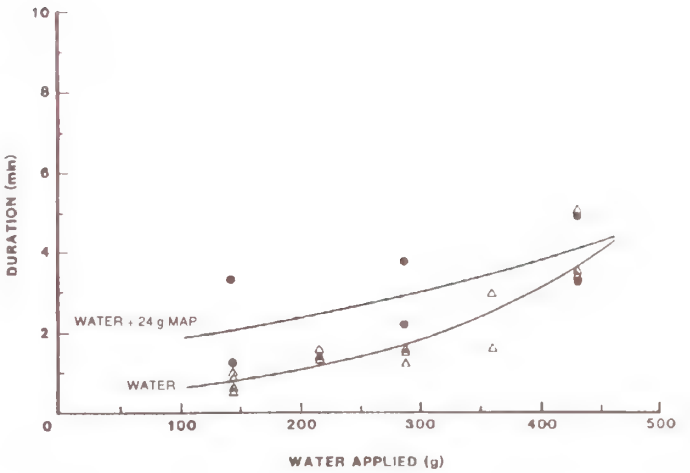

Figure 6—SS2 (duration of combustion recovery) for water, and for water plus MAP.

Figure 6 plots the duration of energy release rate during the recovery to maximum intensity, which was lower than in the untreated fuel. It shows the effects of water alone and water plus MAP on the duration of SS2. As the amount of water/MAP is increased, the duration increases corresponding to a decrease in the intensity of the burning fuel. When 144 g water was applied to the burning fuels, SS2 E_R remained constant for 0.85 minutes. Adding 24 g MAP to the water increased the time to 2.32 minutes, almost threefold. Doubling the water treatment doubled the duration to 1.76 minutes. Adding MAP less than doubled the duration. Tripling the water to 432 g increased the duration to 3.67 minutes; adding 24 g MAP extended the duration only 0.35 minutes. The addition of MAP extended the duration for water, but not to the extent of a larger volume of water, and MAP was less effective at lower concentrations.

Combustion Recovery—Figure 7 plots the time from when the sprayer was turned off until the onset of combustion recovery. Point F (fig. 1) was actually the end of SS1 and the beginning of SS2. The duration indicates the effect of water and chemical on the combustion recovery time. Table 3 lists the treatments and their effects on the time required for the fire to evaporate the water and start to recover to an E_R magnitude, which was controlled by the fuel volume, water, and chemical remaining in and on the fuel when SS1 ended. When 144 g of water was sprayed, 1.12 minutes elapsed before evaporation was sufficient to allow the fire to begin to recover from the lowest E_R. When the treatment was doubled, the time increased to 4.06 minutes, almost fourfold; and when tripled to 432 g water, the time was extended to over sixfold. The addition of 24 g MAP to the water almost tripled the time delay at the 144 g treatment level, and caused a 72 percent increase when the treament was doubled and 56 percent increase when it was tripled. The addition of MAP to water had progressively less effect in delaying combustion recovery as the water volume increased and the solution percentage decreased.

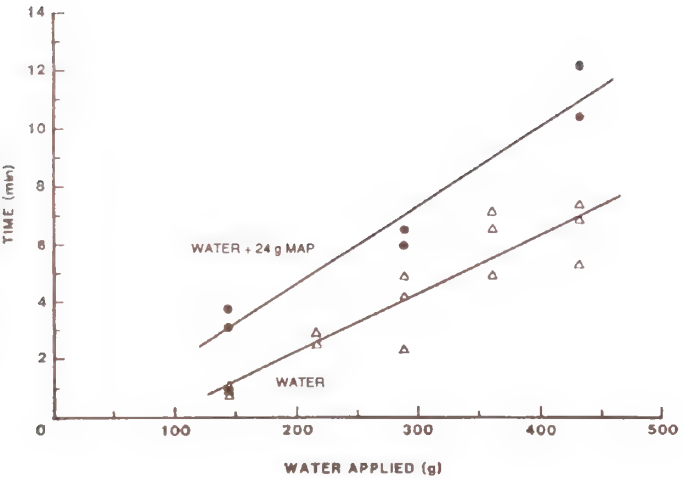

Figure 7—Time to start of combustion recovery for water, and for water plus MAP.

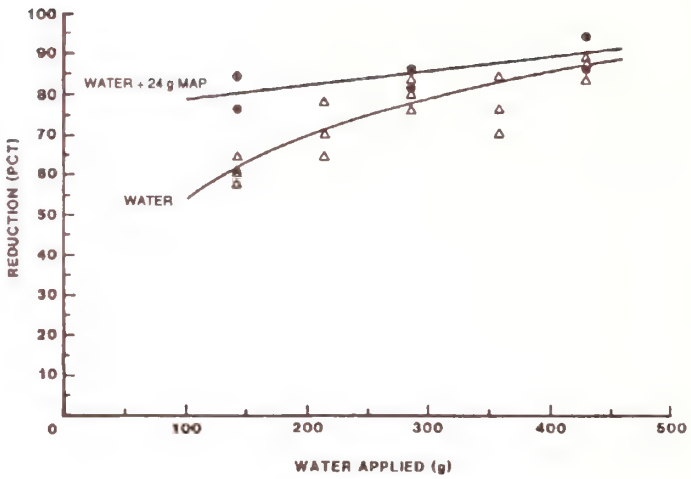

Figure 8—Combustion recovery energy release rate for water, and for water plus MAP.

Maximum Combustion Recovery Magnitude—Even though SS2 indicates the sustained E_R level, the maximum recovery magnitude is also a good measure of how water and chemicals affect energy release. The magnitude to which combustion recovers for the last time before the fuels burn out was measured at point I. Figure 8 shows the reduction in E_R that was reached. The maximum E_R at point I was reduced 62 percent when the burning fuel was sprayed with 144 g of water. Adding 24 g MAP caused an additional reduction of 18.3 percent. Doubling the water improved the reduction by water alone by 15.9 percent. Adding 24 g MAP to the 288 g water reduced the E_R by 85.2 percent. Tripling the water to 432 g increased the reduction 25.2 percent over the basic 144 g water. Twenty-four grams MAP in 432 g water improved the reduction by only 2.8 percent.

Figure 9 plots the times from when the sprayer was turned off until the maximum E_R of SS2 was reached relative to the amount of water and chemical applied to the fire. It shows the elapsed times before the fires were reduced to their lowest intensity and then recovered to the highest energy release rates since treatment was ended. Table 4 lists the E_R and time data derived from the weight loss and irradiation traces. When 144 g water was sprayed onto the burning pine needles, the maximum recovery occurred in 1.7 minutes. Adding 24 g MAP increased the time of recovery 2½-fold. Doubling the water increased the time to 5.02 minutes, and adding 24 g MAP increased the time 61 percent. Spraying 432 g water increased the time to 8.35 minutes, slightly longer than half as much water with MAP added. Adding 24 g MAP increased the time to 12.35 minutes or about 50 percent.

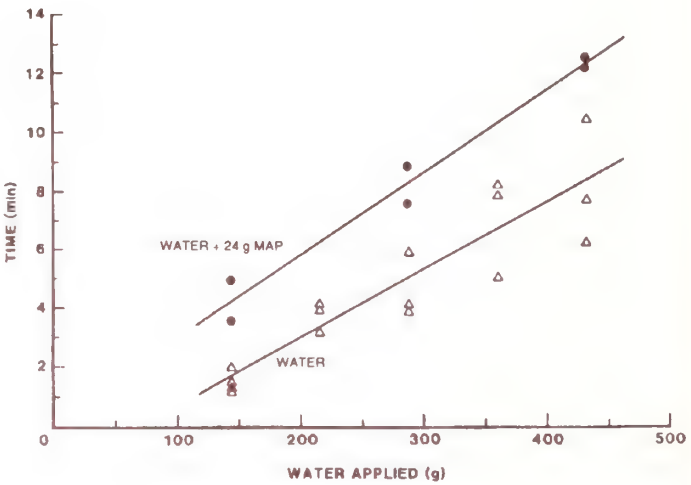

Figure 9—Time to maximum combustion recovery for water, and for water plus MAP.

CONCLUSIONS

Energy Release Reduction

Figure 10 shows a summary of the differences caused by treatments on the energy release rates measured during combustion recovery at the BC, SS1, and SS2 trace segments. Table 5 lists the treatments and the resultant percentage decreases in energy release rates for the three parameters and the differences between effects of water and water plus 24 grams MAP. These data were derived from plots in figures 2, 3, and 5.

The "knockdown" capabilities of the treatments are indicated by their effects on the energy release rate decrease measured at trace segment BC. The BC span of change with increases of 144 to 432 g water + 24 g MAP is 11.8 percent. The BC span of difference in water and water plus MAP is only 0.4 percent (11.4 to 11.8)—meaning very little or no change with increasing penetration and decreasing chemical in each droplet. This indicates that increasing penetration and decreasing concentration make very little difference in fire "knockdown." This would indicate that the "knockdown" is most effective at the surface of the fuel and the chemical involved is of little consequence at that time, or that the effects of the quantity of water overshadow the effects of the decreasing amounts of chemical in each droplet. As a rule of thumb, we can say that water alone, for the amounts applied in

Table 4—Combustion recovery energy release rate data

Fire	Water	MAP	I	I reduction	IT-NT
	- - - - g - - - -		Btu/s	Percent	Min
M28N1	144	0	102.7	61.6	1.22
M28N2	144	0	112.0	58.2	1.53
M28N3	144	0	96.4	60.9	2.00
M28N4	144	0	96.4	65.2	1.37
JUN11N2	144	24	48.2	84.7	4.97
JUN11N3	144	24	51.5	76.8	3.60
JUN8N1	216	0	83.4	70.4	3.20
JUN8N2	216	0	86.7	65.0	3.95
JUN8N3	216	0	51.5	78.7	4.15
JUN9N1	288	0	48.2	80.6	4.15
JUN9N2	288	0	41.8	84.1	3.90
JUN9N3	288	0	54.5	76.5	5.93
JUN11N4	288	24	38.5	82.2	8.85
JUN11N5	288	24	32.1	86.3	7.57
JUN9N4	360	0	32.2	84.7	5.05
JUN9N5	360	0	73.8	70.5	7.88
JUN9N6	360	0	57.8	76.7	8.23
JUN4N1	432	0	28.9	89.2	10.45
JUN4N2	432	0	29.5	87.8	7.73
JUN10N1	432	0	41.8	83.8	6.25
JUN11N6	432	24	16.0	94.1	12.23
JUN11N7	432	24	32.2	86.9	12.55

[1]Is the 6 second average of E_R at the highest recovery rate; IT and NT are the elapsed times for points I and N to occur.

Table 5—Summary of Energy Release Rate Reductions and Durations

Water applied	Energy release rate: Water only reduction	Water only duration	Water + 24g MAP reduction	Water + 24g MAP duration
g	Percent	Min	Percent	Min
		BC		
144	69.5	0.17	76.3	0.17
216	72.0	.17	78.9	.17
288	74.4	.17	81.7	.17
360	77.7	.17	84.8	.17
432	80.9	.17	88.1	.17
		SS1		
144	79.1	0.56	91.4	2.03
216	85.7	1.31	91.9	3.37
288	89.1	2.41	92.6	4.82
360	91.1	3.86	93.4	6.37
432	92.4	5.68	94.1	8.12
		SS2		
144	66.1	0.85	82.3	2.32
216	74.1	1.22	86.6	2.65
288	79.8	1.76	89.6	3.05
360	84.3	2.54	92.0	3.50
432	87.9	3.67	93.9	4.02

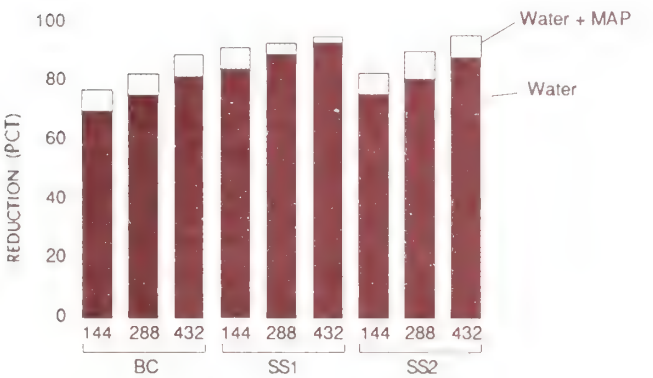

Figure 10—Energy release comparisons—BC (knockdown), SS1 (holddown), and SS2 (recovery).

this study, decreased the energy release rate by 70 to 81 percent and the addition of 24 g MAP caused only an additional 7 percent decrease (table 5).

The fire "holddown" abilities of the treatments are indicated (fig. 10 and table 5) by the decreases in energy release rates and extended times measured for trace segment SS1. The SS1 span of change with increases of 144 to 432 g water is 13.3 percent but only 2.7 percent for increases of 144 to 432 g water plus 24 g MAP. This 10.6 percent difference indicates a moderate improvement with increasing penetration and decreasing chemical in each droplet. It appears that increasing penetration has a very positive effect on "holddown" and the chemical has a lesser effect. Keeping the fire intensity at a reduced level for a longer time appears to be accomplished more effectively by the higher water volumes and by the higher solution concentrations. The retardant chemicals cause increased effectiveness for the low water volumes, much more than for the higher water volumes.

SS2 Magnitude—The magnitude to which the energy release rate returns after most of the water and chemical have been lost is measured by the SS2 segment of the weight trace. The span of change with increases of 144 to 432 g water is a 21.8 percent decrease in the maximum energy release rate. SS2 span of change with increases of 144 to 432 g water plus 24 g MAP is 11.6 percent. The span of differences between water and water plus MAP is 10.2 percent. As with SS1, SS2 shows a moderate change with increasing penetration and decreasing chemical in each droplet. The differences between water only and water plus MAP treatments show that there are definite advantages to the use of chemicals at all levels of treatment, with the least amount of water showing the most significant advantage.

SS1 Duration—The time periods that SS1 and SS2 burn are also indicative of the effects of treatments on burning fuels (table 5). The duration of SS1 (holddown) increased by 10 times when the water-only treatment was tripled from 144 to 432 g. With the MAP solution, the duration increased fourfold for 144 and 432 g water. The time between water and water plus MAP less than doubled from 1.47 to 2.46 minutes at the 432 g level. These data show that the time that the fire intensity was subdued increased by fourfold at the high-chemical-concentration, low-penetration applications, and increased by less than 50 percent at the low-concentration, high-penetration applications.

SS2 Duration—The duration of SS2 (table 5) increased fourfold when the water only treatment was tripled from 144 to 432 g. For the MAP solution the duration increased by less than twice when the water treatment was tripled. The span of difference between water and water plus MAP decreased less than fourfold from 1.47 to 0.35 minutes difference at the 432 g level. Adding MAP at the high water treatment levels does not appear to extend the SS2 duration significantly.

Combustion Recovery

Time Until Start—The delay of the start of the buildup to maximum recovery (during SS1) showed that adding MAP to the water prolonged the low energy output rate. By increasing the water treatment by three times, the delay increased by about sixfold, and by adding 24 grams MAP the delay was increased by 273 percent at the lowest water treatment and by only 56 percent at the highest water treatment. The decrease in added effectiveness caused by MAP was again overshadowed by the increases in water quantity, but at all levels the MAP did add to the delaying effect.

Time to Maximum—The total elapsed time for the burning fuel to be held at a low E_R and then build to its maximum was prolonged by the addition of MAP. Water alone delayed the peak E_R to 1.7 minutes with a 144-g water-only treatment, and to 8.35 minutes (491 percent increase) with a 432-g treatment. Adding MAP to the water increased the delay by 249 percent at the 144-g water level, and only by 148 percent at the 432-g level.

Maximum Magnitude—The addition of MAP to water showed an advantage in decreasing the maximum E_R during the last recovery when the water and MAP were probably at their minimum quantities on the fuel bed. When 144 g water was applied, the maximum E_R was reduced by 62 percent over the maximum when there was no treatment. Adding 24 g MAP reduced the maximum another 18.3 percent. At the higher water treatment levels, the addition of the MAP made a smaller difference but still caused significant reductions in the E_R, that is, 432 g water reduced E_R 87.2 percent and the MAP improved that by only 2.8 percent.

MANAGEMENT APPLICATION

Whether or not a retardant is a short-term (depends solely on water to reduce combustion) or long-term (depends on chemical and water to reduce combustion), the most important consideration is capability to reduce energy release rate. Another important factor is how long the retardant can hold the combustion below an intensity that will support fire spread through treated fuels and thus on into untreated fuels. The data in this study show that the MAP used in currently approved forest fire retardants does increase the capability of water to reduce fire intensity and delay combustion recovery when the retardant is applied directly on the flames. The use of chemical causes the most improvement when used at the highest concentrations or when water is in short supply. As the amount of water increases, the difference between the effectiveness of water alone and water plus chemical decreases to a level where the effect of water quantity overshadows the effects of the chemical.

The objective of this study was to determine if water/chemical mixtures were superior to ordinary water if applied directly to flames of active fires. The data in this study show that there is a significant advantage to using chemicals. The capability of water to immediately reduce flames to smoldering combustion is enhanced only slightly by retardant chemicals. But the chemical significantly reduced fire intensity and extended the times that the flames were reduced as smoldering continued. Chemical retardant can be a definite advantage during direct attack fire suppression efforts .

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APPENDIX A: WEIGHT AND IRRADIATION TRACES FOR FIRES TREATED WITH WATER AND MONO-AMMONIUM PHOSPHATE

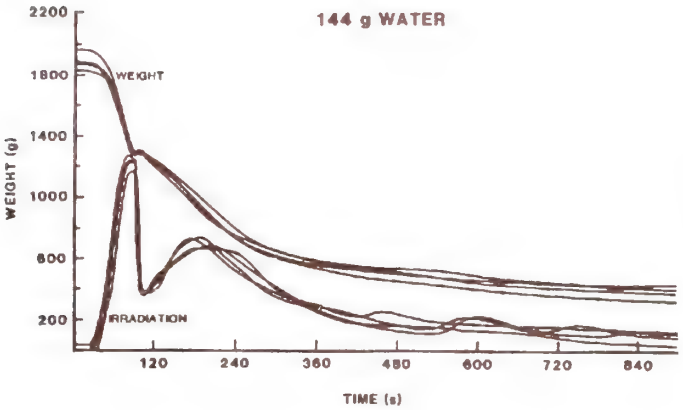


Figure 11—Treatment: 144 g water.

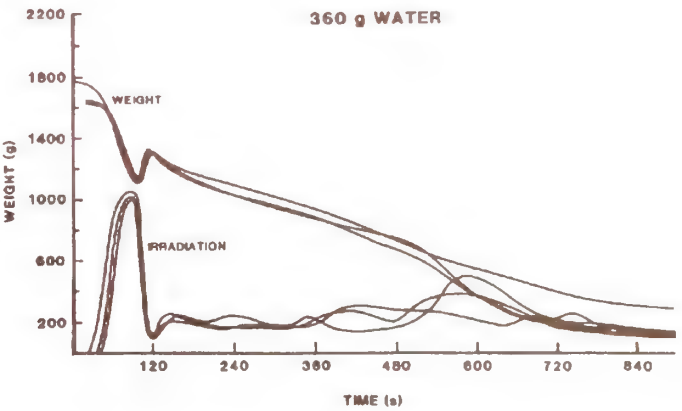


Figure 14—Treatment: 360 g water.

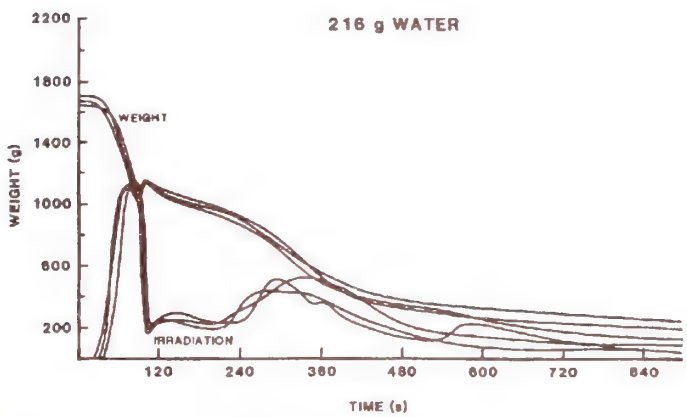


Figure 12—Treatment: 216 g water.

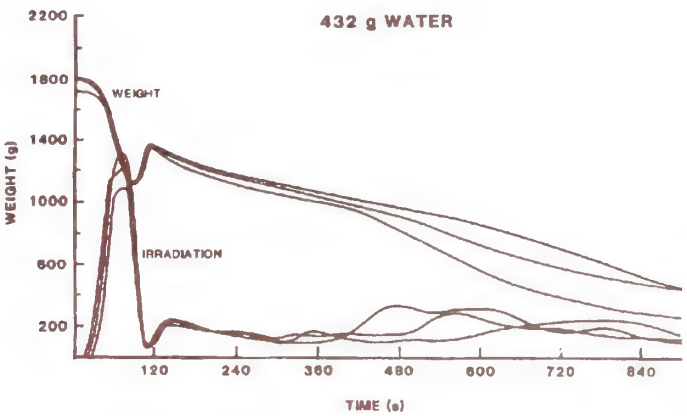


Figure 15—Treatment: 432 g water.

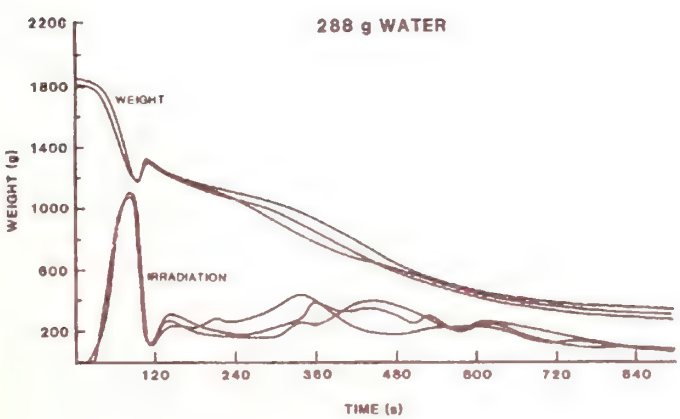


Figure 13—Treatment: 288 g water.

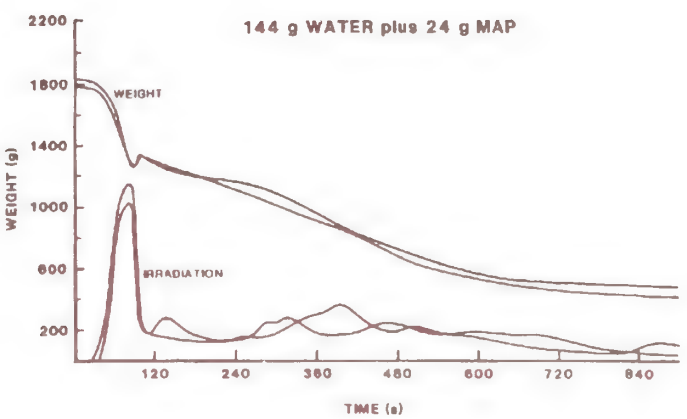


Figure 16—Treatment: 144 g water plus 24 g mono-ammonium phosphate.

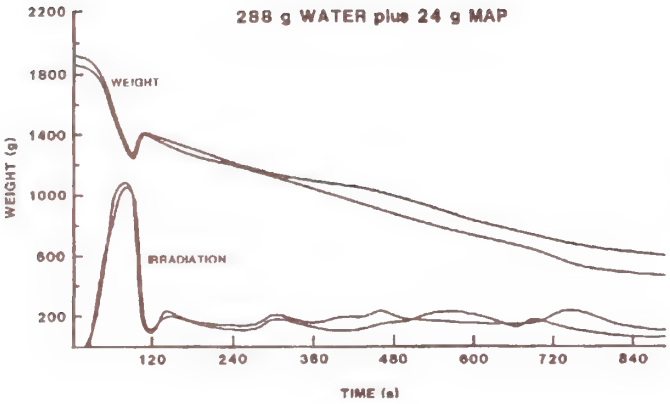


Figure 17—Treatment: 288 g water plus 24 g mono-ammonium phosphate.

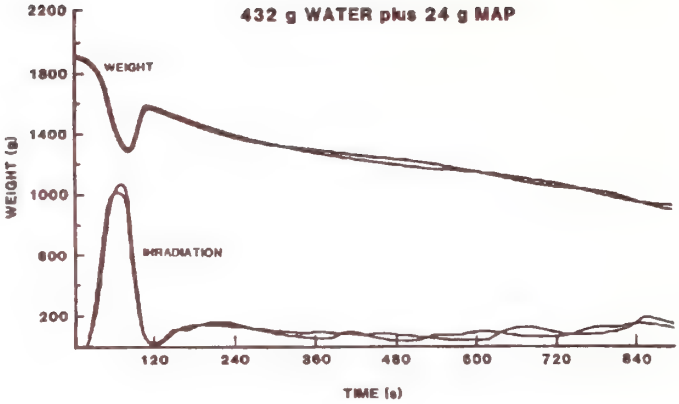


Figure 18—Treatment: 432 g water plus 24 g mono-ammonium phosphate.

APPENDIX B: WEIGHT AND TIMES FROM DESIGNATED POINTS ON WEIGHT TRACES

Table 6—Weight and times from designated points on weight traces[1]

Fire	Water/MAP	A	AT	B	BT	C	CT	D	DT	E	ET
	g/g	*g*	*s*	*g*	*s*	*g*	*s*	*g*	*s*	*g*	*s*
M28N1	144.00	1,164	92	1,139	108	1,073	129	385	440	363	462
M28N2	144.00	1,288	89	1,263	104	1,204	123	425	545	396	575
M28N3	144.00	1,237	82	1,233	97	1,175	120	473	543	444	580
M28N4	144.00	1,245	81	1,157	101	1,087	124			873	177
JUN11N2	144.24	1,300	81	1,296	105	1,234	129	1,161	228	1,193	249
JUN11N3	144.24	1,362	74	1,373	94	1,347	106	1,245	183		
JUN8N1	216.00	1,186	160	1,226	179	1,153	201	998	302		
JUN8N2	216.00	1,109	81	1,135	105	1,095	119	978	208		
JUN8N3	216.00	1,241	80	1,263	99	1,212	116	1,091	202		
JUN9N1	288.00	1,245	82	1,303	111	1,208	138	1,044	252		
JUN9N2	288.00	1,157	96	1,237	121	1,168	148	1,091	189	1,047	214
JUN9N3	288.00	1,186	78	1,245	106	1,172	132	989	279		
JUN11N4	288.24	1,336	80	1,380	114	1,307	140	1,139	277	1,195	303
JUN11N5	288.24	1,267	85	1,347	113	1,263	143	1,128	267	1,084	304
JUN9N4	360.00	1,131	92	1,289	120	1,237	138	987	321	1,069	260
JUN9N5	360.00	1,241	68	1,395	97	1,285	133	919	384		
JUN9N6	360.00	1,219	71	1,373	98	1,281	122	1,000	306	861	394
JUN4N1	432.00	1,274	69	1,354	112	1,281	143	1,091	331	1,055	353
JUN4N2	432.00	1,212	77	1,358	117	1,278	145	1,080	314		
JUN10N1	432.00	1,263	76	1,442	109	1,351	135	1,124	321		
JUN11N6	432.24	1,314	73	1,567	115	1,384	220	1,201	514	1,131	602
JUN11N7	432.24	1,296	74	1,493	120	1,398	172	1,051	623	996	676

[1]A, B, C. . . weight taken at points on the weight trace; AT, BT, CT. . . times on the irradiation trace corresponding to points on the weight trace.

Table 7—Weight and times from designated points on weight traces[1]

Fire	Water/MAP	F	FT	G	GT	H	HT	I	IT	J	JT
	g/g	*g*	*s*	*g*	*s*	*g*	*s*	*g*	*s*	*g*	*s*
M28N1	144.00	1,139	108	1,073	129			853	177	780	193
M28N2	144.00	1,263	104	1,204	123	1,036	165	883	191	671	238
M28N3	144.00	1,233	97	1,175	120	1,022	165	817	212	747	231
M28N4	144.00	1,157	101	1,087	124	937	164	873	177	594	245
JUN11N2	144.24	1,113	280	996	339	959	356	861	393	681	500
JUN11N3	144.24	1,157	253	1,142	258	1,109	273	1,044	302	747	465
JUN8N1	216.00	967	321	945	330			813	367	590	436
JUN8N2	216.00	970	216	953	225	886	257	616	337	422	398
JUN8N3	216.00	1,065	222	1,055	225	923	273	725	344	532	450
JUN9N1	288.00	1,018	273	883	345	897	339	853	354	671	434
JUN9N2	288.00	1,011	234	1,062	205	809	323	740	349	645	398
JUN9N3	288.00	970	298	828	379	718	421	619	457	531	495
JUN11N4	288.24	1,018	376	890	457	985	400	703	636	605	707
JUN11N5	288.24	1,007	419	901	521	886	531	846	559	671	693
JUN9N4	360.00	945	355	934	367	879	394	831	419	638	533
JUN9N5	360.00	839	461	758	500	645	533	502	566	374	614
JUN9N6	360.00	762	463	747	471	616	527	418	589	356	617
JUN4N1	432.00	908	547	700	715	674	733	674	733	487	858
JUN4N2	432.00	872	511	839	532	813	542	755	576	703	613
JUN10N1	432.00	1,047	401	981	439	912	468	890	478	579	637
JUN11N6	432.24	1,051	732	1,003	774	992	787	948	837	927	865
JUN11N7	432.24	934	787	868	850			850	862	809	898

[1]A, B, C. . . weight taken at points on the weight trace; AT, BT, CT. . . times on the irradiation trace corresponding to points on the weight trace.

Table 8—Weight and times from designated points on weight traces[1]

Fire	Water/MAP	K	KT	L	LT	M	MT	N	NT	O	OT
	g/g	*g*	*s*	*g*	*s*	*g*	*s*	*g*	*s*	*g*	*s*
M28N1	144.00	546	275	1,172	92	1,380	77	1,153	104	1,720	23
M28N2	144.00	641	269	1,311	87	1,464	76	1,292	99	1,819	24
M28N3	144.00	612	284	1,270	81	1,449	67	1,252	92	1,815	25
M28N4	144.00	535	273	1,204	83	1,391	70	1,183	95	1,829	19
JUN11N2	144.24	733	475	1,300	81	1,496	69	1,325	95	1,808	22
JUN11N3	144.24	977	346	1,362	74	1,523	60	1,391	86	1,830	21
JUN8N1	216.00	535	463	1,237	157	1,442	143	1,245	175	1,742	
JUN8N2	216.00	338	467	1,087	83	1,267	69	1,146	100	1,669	
JUN8N3	216.00	575	415	1,270	77	1,471	61	1,281	95	1,833	
JUN9N1	288.00	605	469	1,245	82	1,490	63	1,312	105	1,797	
JUN9N2	288.00	623	417	1,197	92	1,442	74	1,252	115	1,768	
JUN9N3	288.00	480	527	1,186	78	1,391	61	1,259	101	1,738	
JUN11N4	288.24			1,311	82	1,479	67	1,395	105	1,848	15
JUN11N5	288.24	769	605	1,292	82	1,438	70	1,362	105	1,870	18
JUN9N4	360.00	524	624	1,172	87	1,336	72	1,296	116	1,756	
JUN9N5	360.00	305	676	1,274	64	1,417	53	1,402	93	1,735	
JUN9N6	360.00	308	654	1,267	67	1,460	52	1,380	95	1,700	
JUN4N1	432.00	484	859	1,226	73	1,449	57	1,362	106	1,786	18
JUN4N2	432.00	696	617	1,212	77	1,413	61	1,362	112	1,793	18
JUN10N1	432.00	539	664	1,318	70	1,519	55	1,446	103	1,793	24
JUN11N6	432.24	916	883	1,380	67	1,563	54	1,581	103	1,881	12
JUN11N7	432.24	824	884	1,321	72	1,512	57	1,512	109	1,819	20

[1]A, B, C. . . weight taken at points on the weight trace; AT, BT, CT. . . times on the irradiation trace corresponding to points on the weight trace.

APPENDIX C: EQUATIONS FOR ENERGY RELEASE RATES AND DURATIONS

Data Plot Equations

BC Equations

Figure	Plot parameters	Equations	Constants		R^2
2.	% reduction vs. water	Y = 1/(A+BX)	A = 0.0154	B = –7.049E–6	0.798
	vs. water/MAP	Y = 1/(A+BX)	A = 0.0140	B = –6.091	.912

SS1 Equations

Figure	Plot parameters	Equations	Constants		R^2
3.	% reduction vs. water	Y = A+B/X	A = 99.050	B = –2.882	0.811
	vs. water/MAP	Y = A+BX	A = 89.733	B = 0.010	.270
4.	duration vs. water	$Y = A*X^B$	A = 1.5E–5	B = 2.116	.846
	vs. water/MAP	$Y = A*X^B$	A = 8.5E–3	B = 1.123	.976

SS2 Equations

Figure	Plot parameters	Equations	Constants		R^2
5.	% reduction vs. water	Y = A+B*log X	A = –32.836	B = 19.898	0.902
	vs. water/MAP	Y = A+B*log X	A = 29.702	B = 10.583	.929
6.	duration vs. water	Y = A*EXP(BX)	A = 0.407	B = 5.08E–3	.830
	vs. water/MAP	Y = A*EXP(BX)	A = 1.535	B = 2.26E–3	.391
7.	sprayer off until start of SS2				
	time vs. water	Y = A+BX	A = –1.821	B = 0.020	.868
	time vs. water/MAP	Y = A+BX	A = –0.878	B = 0.027	.946

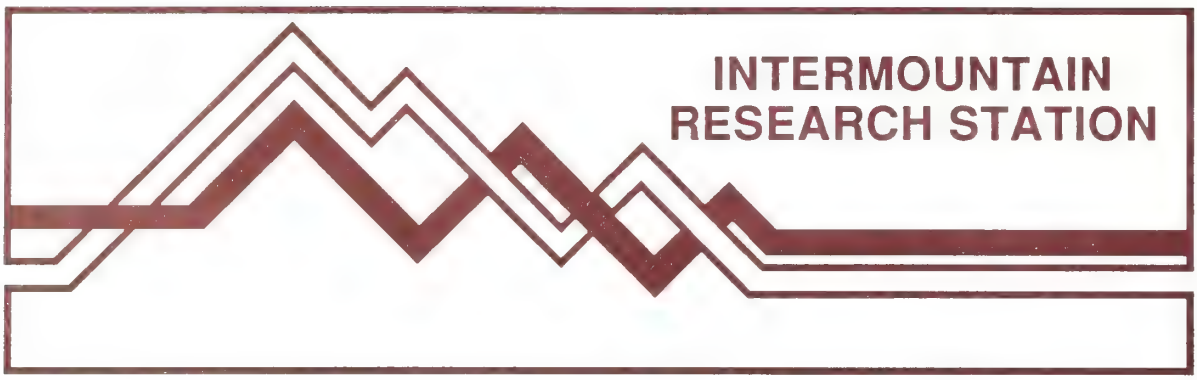
Combustion Recovery Equations

Figure	Plot parameters	Equations	Constants		R^2
8.	% reduction vs. water	Y = A+B*LOGX	A = –52.122	B = 22.962	0.853
	vs. water/MAP	Y = A+BX	A = 75.417	B = 0.033	.583
9.	water vs. time	Y = A+BX	A = –1.630	B = 0.023	.824
	water/MAP vs. time	Y = A+BX	A = 0.190	B = 0.028	.973

Blakely, Aylmer D. 1990. Combustion recovery of flaming pine needle fuel beds sprayed with water/MAP mixtures. Res. Pap. INT-421. Ogden, UT: U.S. Department of Agriculture, Forest Service, Intermountain Research Station. 15 p.

Water alone was the principal agent reducing flaming combustion to smoldering combustion; adding chemical retardant contributed only a slight additional reduction. Water alone was significantly less effective than chemical mixtures in reducing final energy release rates and maintaining reduced rates of fires allowed to recover. Data suggest that water/chemical mixtures are superior to water for extinguishing wildland fire.

KEYWORDS: fire retardant, extinguish, energy release rate, fire behavior, fire management



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Research Paper
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Influence of Nontimber Resources on Timber Sale Characteristics in the Intermountain West

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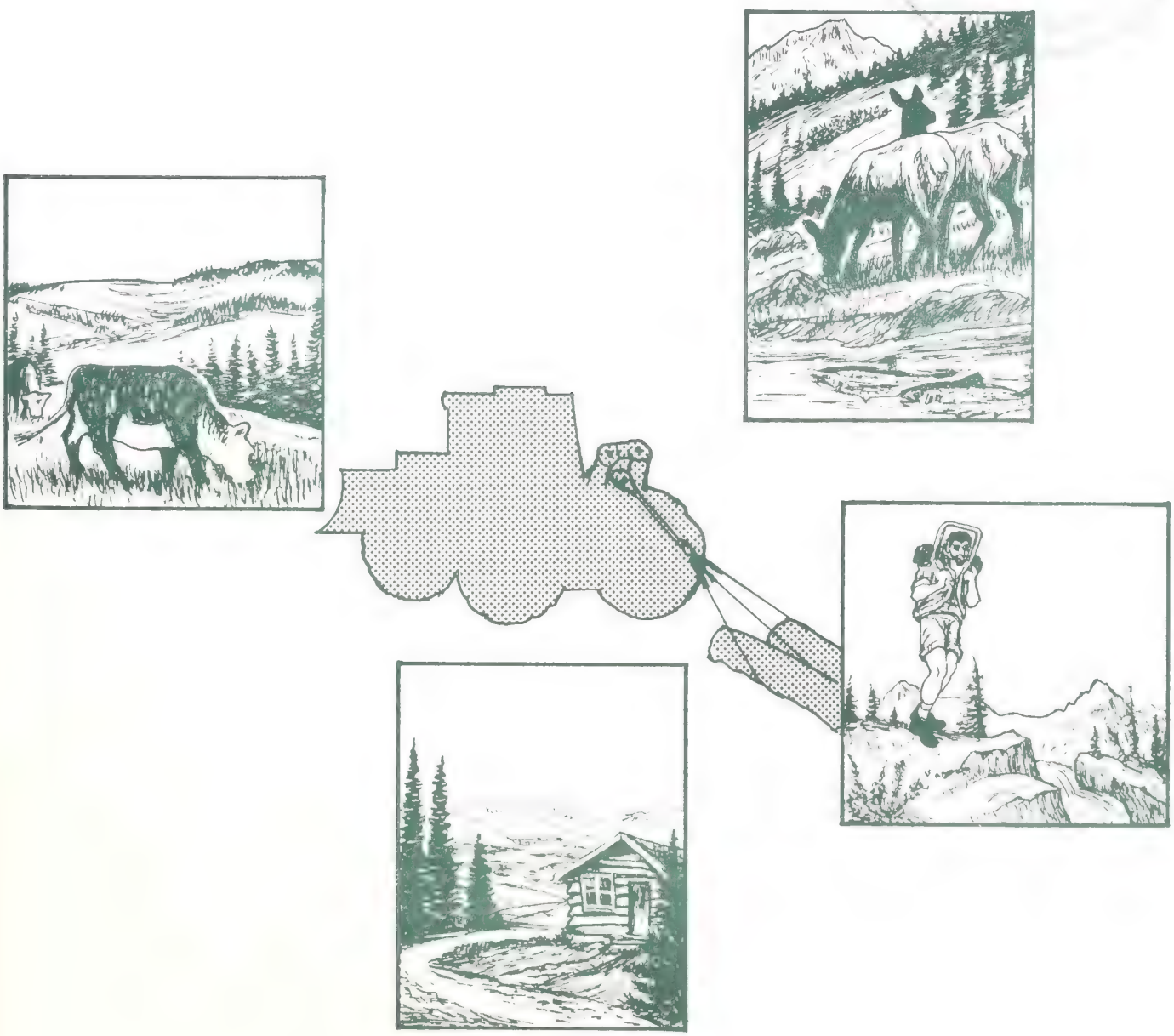
Ervin G. Schuster

UNIVERSITY



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RESEARCH SUMMARY

During the early 1980's, financial aspects of timber sales became a focal point of criticism for the Forest Service, U.S. Department of Agriculture. Gone were the days of the timber sale being viewed solely as a timber management tool. In planning a timber sale, land managers are now required to manage for various nontimber outputs that exist in the forest setting. Arguably, provisions for nontimber outputs are costly and result in an unfavorable financial condition for many sales. But actually, little is known about these relationships.

Based on a sample of timber offerings sold from National Forests in the Northern and Intermountain Regions during 1983-85, this research focused on the influence of the nontimber considerations on establishing timber sale characteristics. The nontimber influence was addressed from the standpoint of nontimber resource motivation, managerial purpose, managerial discretion, the interrelationship between timber sale characteristics, and the cost of provisions for nontimber outputs. Analyses used information from the timber sale reports, appraisal summaries, and questionnaire responses provided by land managers with respect to how timber sale characteristics were changed, the nontimber resource that motivated the changes, and so on. A "timber-only" level was estimated for every timber sale characteristic on each timber sale. Nontimber costs were based on the estimated reduction in stumpage value using the actual and timber-only sale characteristic levels. Factor analysis was used to investigate the linkage between the change in timber sale characteristics and the nontimber motivation.

The wildlife resource was found to be the most important nontimber consideration when setting the level of timber sale characteristics for the Northern and Intermountain Regions; soil influences were second. The sale features and requirements most often modified in the Northern Region consisted of acres harvested, number of cutting units, percentage of volume clearcut, slash removal, and cross ditching. In the Intermountain Region, acres harvested, number of cutting units, volume per acre harvested, seeding of temporary developments, and slash removal were modified most often.

Land managers provided information as to the managerial purpose and discretion that influenced the timber sale characteristic levels. Questionnaire results showed that mitigation was the overwhelming managerial purpose in setting timber sale characteristic levels. Land managers indicated that sale features were voluntarily modified, but modifications of sale requirements were mostly policy based.

Analysis of nontimber costs estimated, in terms of 1985 dollars, that the statistical high bid was reduced by $21.47 and $12.95 per thousand board feet (M bd ft) in the Northern and Intermountian Regions, respectively. Reductions in statistical high bid reflect only revenues forgone, not Forest Service sale preparation and administration costs nor opportunity costs of alternative management practices on the forest land.

Mitigation and policy-based timber sale modifications accounted for a major portion of the reduction in statistical high bid. The reductions attributed to mitigation efforts were $16.36/M bd ft in the Northern Region and $11.55/M bd ft in the Intermountain Region. Policy-based modifications of timber sale characteristics account for $12.74/M bd ft in the Northern Region and $10.58/M bd ft in the Intermountain Region.

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Influence of Nontimber Resources on Timber Sale Characteristics in the Intermountain West

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INTRODUCTION

Since the early 1980's, timber sale economics on National Forests has become an important public policy issue. Labels such as "below-cost," "deficit," and "unsold" are increasingly used to describe the financial condition of timber sales, a condition determined both by market forces and by timber sale design.

The Forest Service, U.S. Department of Agriculture, mainly influences the financial condition of timber sales through its control over sale design. Forest Service managers vary design characteristics in response to both timber and nontimber objectives. Rasmussen (1985) suggests that a direct link exists between below-cost sales and the management of nontimber resources, that forgone revenues resulting from managing nontimber resources should enter the cash-flow analysis of timber sales. Are these modifications costly? Although the propriety of timber sale modification for nontimber purposes is well established in law and tradition, the extent and cost of these modifications is not well understood.

Schuster and others (1984) showed that management of nontimber resources commonly influences timber sale design. They showed that a high percentage of timber sales incorporates provisions to mitigate harvest impacts on nontimber resources, that location and size of cutting units, along with road density and location, are most commonly modified, and much more. And Benson and Niccolucci (1986), in their study of timber sales in northern Idaho and western Montana, showed that stumpage receipts decreased by about 25 percent for protection of nontimber resources when harvesting timber.

Past research, however, has left many questions unanswered. Specifically, it has failed to deal simultaneously with modification of timber sale characteristics as related to nontimber resource motivation, managerial purpose and discretion available to the manager, and the cost of timber sale modifications. That was the task of this study. Specifically, we first addressed the question of modifying timber sale characteristics in terms of the direction of change (increase, decrease, or no change), the nontimber resource motivating the change (timber, wildlife, and so on), the alternative the manager had selected (mitigation or enhancement), the discretion available (voluntary or policy) in determining the modification, and the interrelationship between timber sale modifications. Second, we addressed the cost of timber sale modifications for nontimber purposes in terms of reduced stumpage value.

METHODS

Data used in this study were obtained from timber sale records and through a questionnaire about timber sale design. The questionnaire was sent to timber sale designers in the Intermountain West. From this information, we learned what was and was not done in timber sales, how often, and why. This information was used to construct a "timber-only" characterization of each sale. Through a system-of-equations approach, the difference in stumpage value between the timber-only and actual sale characteristics estimated the cost of provisions for nontimber purposes. Factor analysis was used to better understand the linkage between sale characteristics.

Sampling and Information Collection

Study data were obtained for a random sample of timber offerings on National Forests in the Intermountain West (consisting of the Forest Service's Intermountain and Northern Regions [fig. 1]) sold between October 1982 and September 1985. Initially all sales were sampled. But after preliminary data analysis, it was determined that only sales consisting of 2 million bd ft or larger would be used. These larger timber sales (larger in volume, acres, and development) provide the land manager with the opportunity to manage for the nontimber influence. Final sample size was 137 timber sales in the Northern Region and 87 in the Intermountain Region.

Data were obtained in two stages. In the first stage, information was collected on 36 timber sale characteristics (sale features and requirements) and 12 appraisal cost items, from the timber sale report and timber sale appraisal summary (Forest Service Form 2400-17). The second stage utilized a questionnaire in which the principal timber sale planner identified the nontimber resource influence and the effect the resource had on the timber sale characteristic level. This information was collected for only a subset of the timber sale characteristics because some characteristics, such as paved-haul miles, were not eligible for modification.

The questionnaire focused on each specific timber sale characteristic, one characteristic at a time. It determined the extent to which nontimber considerations influenced decisions about that characteristic. Seven categories were provided to describe nontimber influence, ranging from "none" to "totally nontimber." Realizing that more than one nontimber resource may be affected by a specific

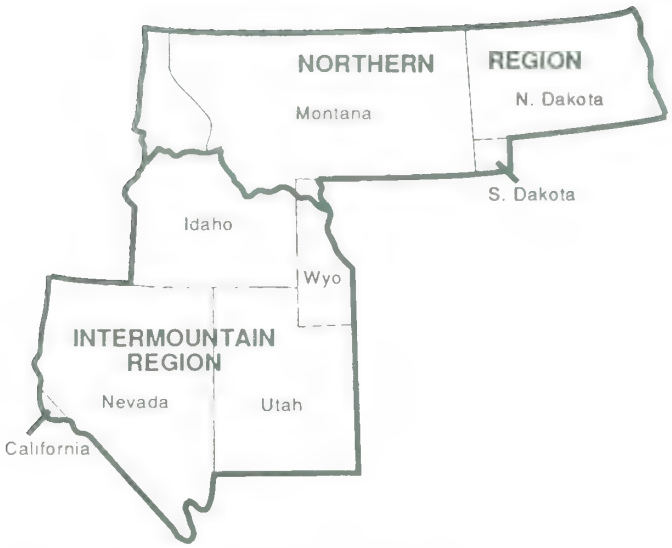

Figure 1—Forest Service's Northern Region and Intermountain Region areas where sale data were analyzed for this study.

modification, we nevertheless asked what was the *primary* (targeted) nontimber resource: visual, recreation, cultural, soil, water, fish, wildlife, or range? We also asked how the sale charcteristic was modified: increased, decreased, or not changed? Finally, we assessed the manager's motivation in modifying timber sales.

Motivation was treated in terms of managerial *purpose* and *discretion*. We determined if the purpose of the timber sale modification was to mitigate, enhance, or a combination:

> Mitigation: To reduce, moderate, avoid, or rectify adverse on-site effects of the timber sale on nontimber resources or to compensate for adverse offsite effects of management actions elsewhere, as in CEQ (1987).
>
> Enhancement: To improve the status (quantity or quality) of a nontimber resource relative to its presale condition.

The amount of managerial discretion was measured by "voluntary" or "policy" choice. A voluntary choice was a discretionary decision made by the sale's planning team. A policy-based choice was one resulting from a policy directive—a formal, written policy requirement, whether in the form of law or agency regulation.

Measuring Modifications of Timber Sale Characteristics

Information obtained from our questionnaire was used to better understand how and why timber sales were modified for nontimber objectives. We did this by (1) conducting a series of general analyses simply intended to describe broad aspects of modifications, (2) developing a timber-only sale design and comparing it to the actual design, and (3) investigating the linkage between changes.

DESCRIBING TIMBER SALE MODIFICATIONS

Questionnaire results provided an enormous amount of detailed information describing which timber sale characteristics were modified and why. This information readily lent itself to cross tabulations. But because cross-tabulation tables are difficult to comprehend, they were converted to frequency tabulations. Illustrations were developed that portray modification frequency by timber sale characteristic for (1) the primary nontimber resource, (2) managerial motivation, and (3) managerial discretion. The frequency indicates the percentage of the timber sales modified—the ratio of the number of sales that were modified to the total number of timber sales from that Region. Five classes ranging from zero to 100 percent were developed and displayed as shaded boxes. A completely shaded box indicates that the sale characteristic has been modified on at least 31 and at most 100 percent of the timber sales. The percentages between 1 and 30 are depicted by boxes that have increasing degrees of shading. Boxes with no shading indicate no activity (zero percent).

ESTIMATING THE TIMBER-ONLY LEVEL

We developed timber-only sale characteristics to better understand how sale characteristics change on behalf of nontimber objectives and to use later in estimating the cost of nontimber provisions. Our estimates of timber-only sale characteristics were based on the land manager's response to our questionnaire. By timber-only, we meant a situation where, for that sale, each sale characteristic was based on timber considerations only. Under the timber-only –scenario, nontimber considerations were absent or were compatible with an exclusive timber orientation. To do this, we identified a subset of sales (for each sale characteristic) where only timber considerations were used in decisions pertaining to the characteristic.

The process began by arranging the timber-only sales in ascending order with respect to the magnitude of the sale characteristic (fig. 2A). The sale characteristic modified for nontimber purposes is mapped into the timber-only

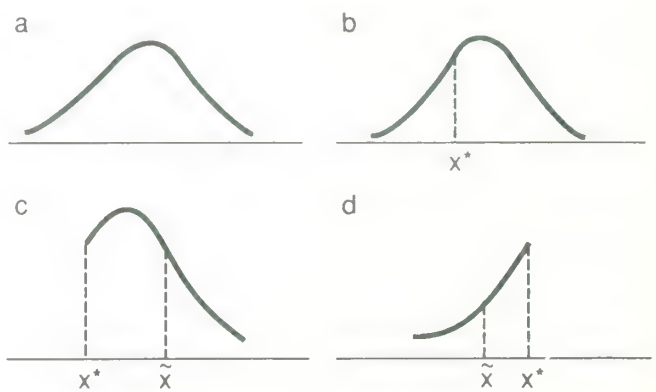

Figure 2—Calculating timber-only sale characteristic level. (a) Timber-only distribution for a specific sale characteristic. (b) The modified sale characteristic (x^*) mapped into the timber-only distribution. (c and d) Calculation of the median ($\tilde{x}$) based upon the direction of modification provided by the planner.

distribution based on its current sale characteristic level (fig. 2B). Using the information provided by sale planners with regard to the direction of the change and the level of the sale characteristic, the median of the remaining timber-only sales was calculated (figs. 2C, 2D). This median was then used as the estimated timber-only level for that particular timber sale characteristic. The median was selected as the best estimator of central tendency because of the possibility of a skewed distribution (Steele and Torrie 1960).

LINKING SALE CHARACTERISTICS

Do timber sale modifications for nontimber purposes occur individually or in groups or packages of modifications? Presumably, certain timber sale characteristics, such as volume per acre harvested and percentage of the volume clearcut, are related. But simple tabulations can describe only individual occurrences, not combinations; tabulations cannot adequately portray how modifying these timber sale characteristics addresses nontimber purposes. We used the technique of "factor analysis" to better understand the linkage between timber sale modifications.

Factor analysis is a statistical method used to investigate the data covariance structure (see Johnson and Wichern 1982). We used it to explore and detect patterns of association among variables with a view to discovering the link between timber sale modifications. The exploration and detection of the patterns were based on the correlation matrix. The desired result is for a particular group (factor) of variables to be highly correlated among themselves but have relatively small correlations with variables in a different group (factor).

The factor loadings are an important piece of information generated by factor analysis. Factor interpretation is based on the factor loadings and the variables that "load" highly on a particular factor. The factor loadings indicate which variables (timber sale modification) are related to a particular factor. For example, volume per acre harvested and the percentage of the volume clearcut are related. The factor analysis result expected is a factor with large loadings corresponding to volume per acre harvested and percent volume clearcut. Factor interpretation in this study was assisted by using the primary nontimber resource which influenced the modification of the timber sale characteristic.

Estimating Costs of Nontimber Provisions

The cost of the nontimber influence (objective 2) was addressed using a system-of-equations approach. Costs were estimated as the loss in stumpage value resulting from timber sale modifications made for nontimber purposes. This loss was estimated by the difference in stumpage value "with" and "without" nontimber provisions. We used each sale's timber-only characterization as the "without" and the actual characteristics as the "with."

To estimate stumpage value, we created a system of equations that paralleled the residual value (RV) appraisal system used in Forest Service stumpage appraisal. In RV, the value of stumpage is estimated as final product value less all production and logging costs. We posited that timber sale modifications for nontimber purposes affect logging costs, and changes in logging costs are directly reflected in changes in stumpage value.

We represented the cost portion of the stumpage appraisal system by six regression equations. Five of these equations modeled five general phases or types of logging costs. The sixth equation estimated the amount by which the winning bid on each sale exceeded the sale's advertised rate; this is termed "overbid." Costs for each logging phase and stumpage appraisal overbid were treated as dependent variables; timber sale characteristics were the independent variables. The six models used were:

1. Stump-to-truck costs
2. Transportation costs
3. Slash costs
4. Specified road costs
5. Temporary road costs
6. Stumpage appraisal overbid.

The coefficients of the six-equation system could have been estimated using ordinary least squares (OLS), one equation at a time. But stump-to-truck activities could have an effect on slash and temporary road activities and vice versa. This possible interrelationship between logging phases means that the statistical error terms of these activities (logging phases) might be correlated and the equations might not be independent. Given this possible correlation, OLS should not be used. The technique of Seemingly Unrelated Regression solves the problem of correlated error terms and permits simultaneous estimation of the coefficients. The resulting coefficients are statistically efficient (see Kmenta 1971).

The cost and stumpage overbid equations allowed us to estimate expected stumpage price (high bid). Effective purchaser road credits are subtracted from the estimated high bid. This value, statistical high bid (SHB), was considered a better approximation of the revenues returned to the treasury. If SHB fell below the base rates, the SHB was adjusted for base rates (see USDA FS 1977). All dollars were expressed in 1985 value based on the GNP Implicit Price Deflator (BOC 1987).

RESULTS AND DISCUSSION

Research findings concerning nontimber influences on timber sale characteristics will (1) describe modifications made to timber sales on behalf of nontimber concerns and (2) discuss the cost of these modifications. Modifications will be viewed from the standpoint of managerial purpose, managerial discretion, and nontimber resource influence motivating the timber sale characteristic level. Using the information provided by land managers, we present the timber-only depictions for each timber sale characteristic. These depictions were used to estimate the change in timber sale stumpage value—our measure of costs.

Table 1 is a listing of timber sale characteristics used in this study. Characteristics are grouped into three categories: sale features, sale requirements, and dependent variables and other characteristics. Sale requirements are measured in terms of a 0 or 1. The 0 indicates the

Table 1—Timber sale characteristics

Characteristics	Description	Units
Sale features		
VPA	Volume per acre harvested	M bd ft
ACRES	Acres harvested in sale	Acres
%CC	Percent volume clearcut, seedtree, or right-of-way	Percent
%GSL	Percent volume group selection	Percent
%TRA	Percent volume tractor yarded	Percent
#UNIT	Number of cutting units	Number
RECON	Road reconstruction	Miles
NEW	New road construction	Miles
STEEP	Harvested acres >55% slope	Acres
MID	Harvested acres 35-55% slope	Acres
FLAT	Harvested acres 0-35% slope	Acres
CL	Timber sale contract length	Months
TEMP	Temporary road construction	Miles
YT	Average maximum tractor yarding	Feet
YC	Average maximum cable yarding	Feet
CSP	Corridor spacing	Feet
CWD	Corridor width	Feet
DFEL	Percent volume directional felled	Percent
HP	Percent sale area requiring hand piling of slash	Percent
TOTVOL	Total sale volume harvested	M bd ft
Sale requirements		
GATE	Gates and fences required	1 = Yes; 0 = No
SEED	Seeding of skid trails, temporary roads, and landings	1 = Yes; 0 = No
ACCESS	Road access control	1 = Yes; 0 = No
PLANT	Seed or plant for wildlife cover	1 = Yes; 0 = No
SLASH	Slash removal on trail or streams	1 = Yes; 0 = No
DUSTR	Dust control restrictions	1 = Yes; 0 = No
SNAG	Leave or develop wildlife snags	1 = Yes; 0 = No
HAULRES	Log hauling restrictions	1 = Yes; 0 = No
XDITCH	Cross-ditching or waterbars required	1 = Yes; 0 = No
Dependent variables and other characteristics		
Stump-to-truck	Stump-to-truck costs	Total dollars
Transport	Transportation costs	Total dollars
Slash	Slash costs	Total dollars
Temp Roads	Temporary road costs	Total dollars
Spec Roads	Specified road costs	Total dollars
Bid Premium	High bid--advertised rate	Total dollars
ADBH	Average tree diameter	Inches
UHAUL	Unpaved haul distances	Miles
PHAUL	Paved haul distances	Miles
#BIDS	Number of bidders	Number
SPLS	Selling price, log scale	$ per M bd ft
SMETH	Timber sale auction type	1 = Sealed; 0 = Oral
PMETH	Pricing method of contract	1 = Escalated; 0 = Flat rate

requirement was absent, and the 1 indicates present. Sale features were measured in continuous units, such as acres, feet, months, and so on. All sale features and all sale requirements were eligible for modification. The total sale volume (TOTVOL) is the product of VPA and acres harvested (ACRES); it is modified through VPA or ACRES. The third category (dependent variables and other characteristics) consists of (1) the dependent variables for the six stumpage appraisal equations and (2) the other sale characteristics used in the stumpage appraisal equations which were not eligible for modification.

Modification of Timber Sale Characteristics

Land managers establish the level of a timber sale characteristic in response to a variety of timber and nontimber resource concerns. Some modifications are made to enhance nontimber resources, others to mitigate against damage. Some are made voluntarily; others result from a policy requirement.

DESCRIPTION OF TIMBER SALE MODIFICATIONS

Table 2 shows the frequency of sale modification, measured by three categories of change: increase, decrease, and no change. By change, we are referring to change from the timber-only level. Land managers indicated whether the actual sale characteristic level had been changed from what would have been done because of the nontimber influence. Hence, table 2 strictly documents the manager's response and does not involve statistical estimation.

Inspection of "no change" columns of table 2 (those under "0") supports two impressions. First, the vast majority of sale characteristics are not changed for nontimber purposes. For example, in better than 96 percent of the sales, decisions concerning corridor width (CWD) were not influenced by nontimber considerations—they were based on timber considerations only. Second, compared to the Northern Region, the Intermountain Region had more sale features and sale requirements not changed for nontimber purposes. In fact, 14 of the 19 sale features and seven of the nine sale requirements had a higher percentage of no modifications for the nontimber purpose.

Table 2 also shows substantial consistency between the Northern and Intermountain Regions regarding frequency of modification for the timber sale characteristics used in this study. For example, modifications made to the number of acres (ACRES), the number of cutting units (#UNIT), and the volume harvested per acre (VPA) were the most commonly modified sale features in both regions. Similarly, seeding skid trails (SEED), planting for wildlife cover (PLANT), and cross-ditching (XDITCH) were the most frequently modified sale requirements.

Although relatively few timber sale features and requirements are modified for nontimber purposes, when modified the magnitude of sale features tends to be lowered and the sale requirements tend to be increased. Table 2 shows that decreases in VPA, ACRES, and #UNIT are quite common, occurring in both the Intermountain

Table 2—Frequency of timber sale modification, by direction of change

Timber sale characteristics	Intermountain Region Percentage of sales			Northern Region Percentage of sales		
	+[1]	–	0	+	–	0
Sale features						
VPA	2.3	39.1	58.6	2.9	36.5	60.6
ACRES	3.4	71.3	25.3	6.6	75.9	17.5
%CC	1.1	27.6	71.3	10.9	31.4	57.7
%GSL	3.4	3.4	93.1	4.4	5.8	89.8
%TRA	2.3	8.0	89.7	4.4	21.9	73.7
#UNIT	20.7	32.2	47.1	24.1	38.7	37.2
RECON	6.9	9.2	83.9	8.0	13.1	78.8
NEW	8.0	18.4	73.6	8.8	29.9	61.3
STEEP	2.3	29.9	67.8	7	10.9	88.3
MID	4.6	23.0	72.4	2.2	18.2	79.6
FLAT	2.3	11.5	86.2	5.1	13.1	81.8
CL	2.3	12.6	85.1	7.3	21.2	71.5
TEMP	10.3	10.3	79.3	2.9	17.5	86.9
YT	9.2	3.4	87.4	14.6	3.6	81.8
CSP	1.1	1.1	97.7	5.8	0	94.2
YC	0	1.1	98.9	15.3	4.4	80.3
DFEL	16.1	1.1	82.8	24.1	0	75.9
CWD	0	3.4	96.6	0	3.6	96.4
HP	19.5	1.1	79.6	11.7	0	88.3
Sale requirements						
GATE	10.3	0	79.3	8.0	0	92.0
ACCESS	58.6	0	41.4	79.6	0	20.4
DUSTR	81.6	0	18.4	78.8	0	21.2
SEED	92.0	0	8.0	87.6	0	12.4
PLANT	16.1	0	83.9	75.9	0	24.1
SLASH	82.8	0	17.2	91.2	0	8.8
XDITCH	58.6	0	41.4	79.6	0	7.3
SNAG	70.1	0	29.9	75.9	0	24.1
HAULRES	28.7	0	71.3	35.8	0	64.2

[1] + = characteristic increased; – = characteristic decreased; 0 = characteristic not changed.

and Northern Regions. The sale characteristics show that under the timber-only scenario the timber sale would have been larger, both in acres and volume harvested. But in certain cases, increasing the level of a sale characteristic can allow for management of the nontimber influence. For example, average yarding distance (YT), directional felling (DFEL), and hand piling slash (HP) are commonly increased to manage for nontimber resources.

The sale requirements (often termed "c-clauses," referring to clauses in the timber sale contract), such as slash removal (SLASH) and seeding skid trails (SEED), are widely used to manage for the nontimber influence in the Northern and Intermountain Regions. Sale requirements used to manage nontimber resources often restrict logging activities.

TIMBER-ONLY SALE CHARACTERISTICS

Results from our analysis of timber-only sale characteristics provide more definitive estimates of how timber sale characteristics are changed. Note that the timber-only level of a sale characteristic is unaffected by nontimber influences. The actual level is set by the timber sale planning team, reflecting the influence of the nontimber considerations.

Table 3 presents the average timber-only and actual levels for the timber sale characteristics used in this study. In general, the average timber-only level for sale features is higher than the actual level. The lower actual value indicates that the planner decreases these sale characteristics to manage for the nontimber influence. For example, the average number of acres harvested in a timber sale (ACRES) decreased from about 566 acres to 405 acres in the Northern Region and from about 1,114 acres to 800 acres in the Intermountain Region. But not all sale features were lowered, on average. The percentage of the sale volume with directional felling (DFEL) and the average maximum tractor yarding distance (YT) increased substantially in both Regions. Increasing a timber sale characteristic can be used to protect the nontimber influence, but one must have in mind tradeoffs among timber sale characteristics. For example, an increase in YT allows a decrease in miles of temporary and specified road construction. Avoiding road construction may be viewed as more beneficial in comparison to longer tractor yarding distances.

Table 3—Average magnitude of timber sale characteristics for actual and timber-only sale designs

Timber sale characteristics	Intermountain Region		Northern Region	
	Actual	Timber-only	Actual	Timber-only
Sale features				
VPA	10.28	10.95	20.37	24.49
ACRES	800.03	1,113.70	404.77	565.91
%CC	46.31	55.87	69.70	82.83
%GSL	4.03	3.57	2.80	1.10
%TRA	86.69	87.07	56.93	67.75
#UNIT	21.81	22.66	17.35	15.53
RECON	1.92	1.86	1.87	1.87
NEW	2.56	2.74	3.54	3.76
STEEP	50.40	69.26	47.50	49.08
MID	134.15	182.12	120.04	124.39
FLAT	582.83	656.64	236.33	245.81
CL	48.05	50.11	47.15	49.90
TEMP	1.44	1.40	1.06	1.22
YT	659.29	649.64	672.26	634.08
CSP	56.32	54.02	56.64	50.11
YC	371.64	378.54	678.09	612.42
DFEL	38.45	29.25	32.40	21.29
CWD	6.44	6.61	4.36	6.26
HP	3.16	2.24	.76	.41
Sale requirements				
GATE	.41	.11	.09	.01
ACCESS	.59	0	80	0
DUSTR	.82	0	.79	0
SEED	.92	0	88	0
PLANT	.16	0	.24	0
SLASH	.83	0	.91	0
XDITCH	1.00	0	.93	0
SNAG	.70	0	.76	0
HAULRES	.29	0	.36	0

The sale requirements are also used to manage for the nontimber influence. And generally speaking, under the timber-only scenario these requirements would not be implemented. But table 3 also shows, according to timber sale planners, some sale requirements would be required even under a timber-only approach. In our case, the requirement of gates and fences (GATES) occurred in some timber-only sale designs.

NONTIMBER RESOURCES

Figure 3 shows the nontimber resource primarily responsible for motivating changes from timber-only to the actual level of timber sale characteristics, as viewed by the land managers. Three types of information are displayed. First, visual inspection of the overall shading in figure 3 again indicates (1) that most timber sale characteristics are not altered by nontimber considerations (the large amount of white space in the figure) and (2) that when modifications occur, wildlife is most commonly identified as the primary nontimber resource influencing timber sale characteristic levels (the large amount of dark shading). Similarly, there is almost no shading for the fish resource, the cultural resource, or the range resource. This indicates that these resources rarely influence decisions about levels of timber sale characteristics. There are notable exceptions, such as the range resource being somewhat more influential in the Intermountain Region.

The other two types of information shown in figure 3 involve inspection of the individual columns and rows. By inspecting the *columns*, one can determine what tools are

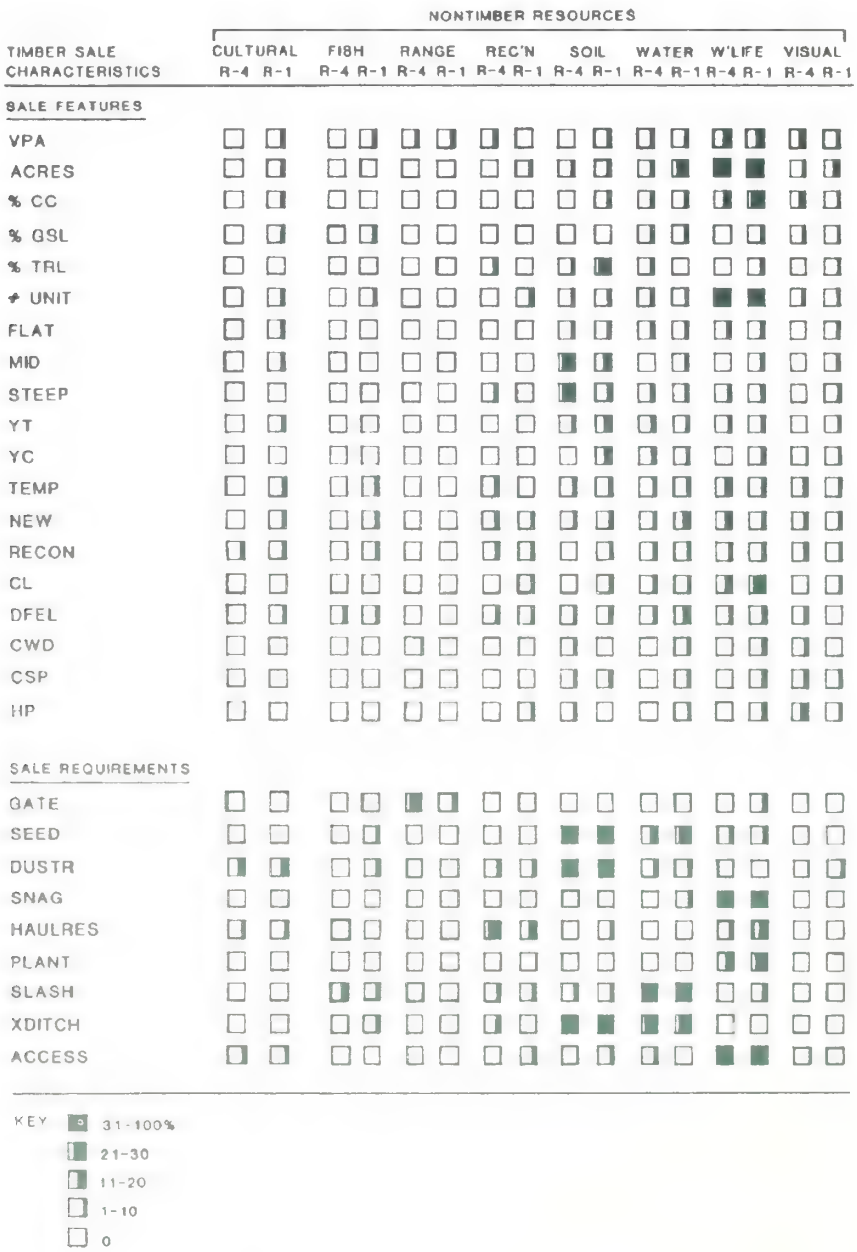

Figure 3—Percent modification for nontimber influences, by nontimber resource (R-4: Intermountain Region, R-1: Northern Region).

used to manage specific nontimber resources. One impression generated is that although many tools are often used to manage a specific nontimber resource, a few tools typically dominate. For example, in the case of wildlife resources, both sale features and sale requirements are used. In the Northern and Intermountain Regions, wildlife considerations are most commonly managed by modifying sale features, such as the amount of acres harvested (ACRES) and the number of cutting units (#UNIT), or sale requirements, such as requiring that snag or wildlife trees (SNAG) be left and restricting access to the sale area (ACCESS). In the case of water resources, management is accomplished almost entirely through sale requirements—restrictions placed on the sale. Cross-ditching roads and trails (XDITCH); seeding roads, trails, and landings (SEED); and removing slash from trails or streams (SLASH) are required on the vast majority of timber sales in the Northern and Intermountain Regions to manage for water resources.

By inspecting the *rows* of figure 3, one can determine what nontimber resource is typically targeted when a specific tool is used. The dominant impression from this analysis is that most tools are used to manage several nontimber resources, not necessarily at the same time, although that is certainly possible. For example, figure 3 indicates that dust control (DUSTR) is modified for the cultural and soil resource. Dust control is usually required adjacent to residential areas or public campgrounds for the purpose of maintaining air quality, and simultaneously accomplishing soil protection by decreasing the erosion potential. Requiring gates and fences (GATES) seems to be an exception of tools being multipurpose; it is used almost exclusively in management of range resources.

LINKAGE BETWEEN SALE CHARACTERISTICS

A timber sale consists of many sale characteristics. In a sense, each characteristic can be viewed as an independent activity. Nevertheless, many characteristics within a timber sale are interrelated. They are used in conjunction, one with another. They are applied as a package. Knowledge of the interdependency leads to a better understanding of how modification of timber sale characteristics is used as a tool to manage nontimber resources. Factor analysis was used to better understand these relationships. This analysis was based on the difference between the actual and timber-only levels for each sale characteristic. Use of the primary nontimber influence, as identified by managers, facilitates understanding and interpretation.

Table 4 shows that nine combinations of sale characteristics were identified for the Northern Region and eight combinations were identified for the Intermountain Region. About half of the packages consist of two-characteristic combinations, the others being either three- or four-characteristic packages. We also show the primary nontimber resource associated with each sale characteristic and the overall direction of change (+, –, or 0) for each characteristic to better understand how these packages of sale characteristics are used in nontimber management. Only about one-fourth of the sale characteristics studied did not belong to a package. Our research suggests that those characteristics are used individually, with no systematic link to other characteristics.

Table 4 shows that some packages are primarily oriented toward one nontimber resource. For example, decisions in the Northern Region concerning the amount of sale area between 35 and 55 percent slope (MID), the amount of sale area in greater than 55 percent slope (STEEP), and requiring cross-ditching (XDITCH) form a package. That is to say, when one of these characteristics is modified in a sale, the other two are also likely to be modified. In this package, MID and STEEP are decreased and XDITCH is increased, all with the soil resource being the primary target. Harvesting on MID and STEEP ground can increase soil erosion. Decreasing the number of acres on these slopes is a means of accounting for the soil resource influence, as is requiring the use of cross-ditching on steeper slopes. Similarly, in the Intermountain Region the average maximum cable yarding distance (YC), the contract length (CL), and the volume per acre (VPA) are commonly decreased as a package, all with wildlife being the primary nontimber resource target.

But table 4 also shows identical packages of timber sale characteristics aimed at different nontimber resources. In the Northern Region, corridor spacing (CSP) and corridor width (CWD) are often changed together, but they are aimed at different primary targets, the soil and visual resource, respectively. Corridor spacing and width also form a package in the Intermountain Region, but managers indicated they were primarily motivated by visual considerations only. The Intermountain Region also has mixed-target packages.

MANAGERIAL MOTIVATION—PURPOSE AND DISCRETION

Managerial Purpose—Given that sale characteristics are modified to manage for the nontimber considerations, we next describe those considerations in terms of managerial purpose: mitigation and enhancement. Generally speaking, mitigation is preventing or moderating damage to a nontimber resource while enhancement actually improves it.

Figure 4 presents the results pertaining to managerial purpose. By inspection, one can quickly conclude that mitigation of the nontimber influence is the dominant motivating factor when modifying the timber sale characteristic. And of the two types of sale characteristics used in mitigation, sale requirements dominate. SEED, DUSTR, SNAG, SLASH, XDITCH, and ACCESS are used in both Regions on at least 31 percent of the sales. These contract clauses mitigate the damaging effect of skid trails and temporary roads by requiring seeding and cross-ditching, controlling dust on haul roads, assuring that wildlife trees are either developed or left, cleaning of slash in streams and trails, and restricting access to the harvested area. The remaining contract clauses are implemented on less than 31 percent of the timber sales.

Mitigation is also the dominant motivation behind changing timber sale characteristics. In the Intermountain and Northern Regions, volume per acre harvested (VPA), the number of acres harvested (ACRES), percent volume clearcut (%CC), the number of cutting units (#UNIT), and the miles of new road construction (NEW)

Table 4—Timber sale characteristics packages, with direction of change and primary nontimber resource

Intermountain Region			Northern Region		
Timber sale characteristics	Change[1]	Primary nontimber resource	Timber sale characteristics	Change	Primary nontimber resource
YC	–	WILDLIFE	MID	–	SOIL
CL	–	WILDLIFE	STEEP	–	SOIL
VPA	–	WILDLIFE	XDITCH	+	SOIL
CSP	+	VISUAL	CSP	+	SOIL
CWD	–	VISUAL	CWD	–	VISUAL
DUSTR	+	SOIL	%CC	–	WILDLIFE
SLASH	+	WATER	VPA	–	WILDLIFE
SEED	+	SOIL			
TEMP	+	WILDLIFE	SLASH	+	WATER
YT	+	SOIL	DUSTR	+	SOIL
GSL	+	VISUAL	GATE	+	RANGE
ACCESS	–	WILDLIFE	SNAG	+	WILDLIFE
GATES	+	RANGE	ACRES	–	WILDLIFE
RECON	–	WATER	TEMP	+	SOIL
FLAT	–	WILDLIFE	YC	–	SOIL
MID	–	SOIL			
PLANT	+	WILDLIFE			
NEW	–	WILDLIFE	NEW	0	WATER
SNAG	+	WILDLIFE	RECON	–	WATER
HAULRES	+	REC	HAULRES	+	WILDLIFE
TRL	–	SOIL	GSL	+	WILDLIFE
			PLANT	+	WILDLIFE
			#UNITS	+	WILDLIFE
			DFEL	+	WATER
			CL	–	WILDLIFE

[1] + = increase; – = decrease; 0 = no change.

are sale characteristics most often modified to mitigate the harvesting activity. VPA and ACRES can be used separately or in combination to mitigate. For example, harvesting fewer acres and less volume per acre leads to a timber sale having less impact in total volume and number of acres harvested. Modifying the percentage of volume clearcut allows one to mitigate the harvesting activity by decreasing the volume harvested per acre (similar to VPA) and the number of acres that are cleared of standing volume. The number of cutting units (#UNIT) also relates to sale size, and its mitigating effect is similar to VPA and ACRES. Modifying the miles of new road construction (NEW) has the mitigating effect of restricting the nonroaded areas that would be opened to timber and other resource management.

But nontimber enhancement does occur, though less frequently than mitigation. In the Northern and Intermountain Regions, sale features, such as volume per acre harvested (VPA) and acres harvested (ACRES), along with new (NEW) and reconstructed (RECON) road building, are modified to enhance the nontimber resource. Sale requirements, such as wildlife snags (SNAG), planting for wildlife cover (PLANT), and access control (ACCESS), are modified to enhance nontimber resources in both Regions.

In general, figure 4 indicates that timber sale characteristics are only occasionally modified to enhance nontimber resources. At most, only 1 to 10 percent of the timber sales was modified for enhancement purposes. The low percentage of timber sales modified for enhancement may be a conservative estimate, however, because the land manager's response considered only the primary resource. It is possible to enhance the timber resource (the primary resource) and also indirectly enhance a nontimber resource. This occurrence would not appear in the percentages presented in figure 4. The mitigation responses are not similarly affected because mitigation is a direct action taken to protect a specific resource.

Managerial Discretion—Another aspect of the manager's motivation deals with the latitude available in modifying a timber sale characteristic to manage for the nontimber influence. Decision-making discretion was measured only as being voluntary (unconstrained) or as policy-based (a requirement).

Figure 5 presents the results pertaining to managerial discretion. The figure indicates that most modifications are voluntarily made in the Intermountain and Northern Regions (darker shading in the voluntary column). Of the timber sale characteristics voluntarily modified, sale

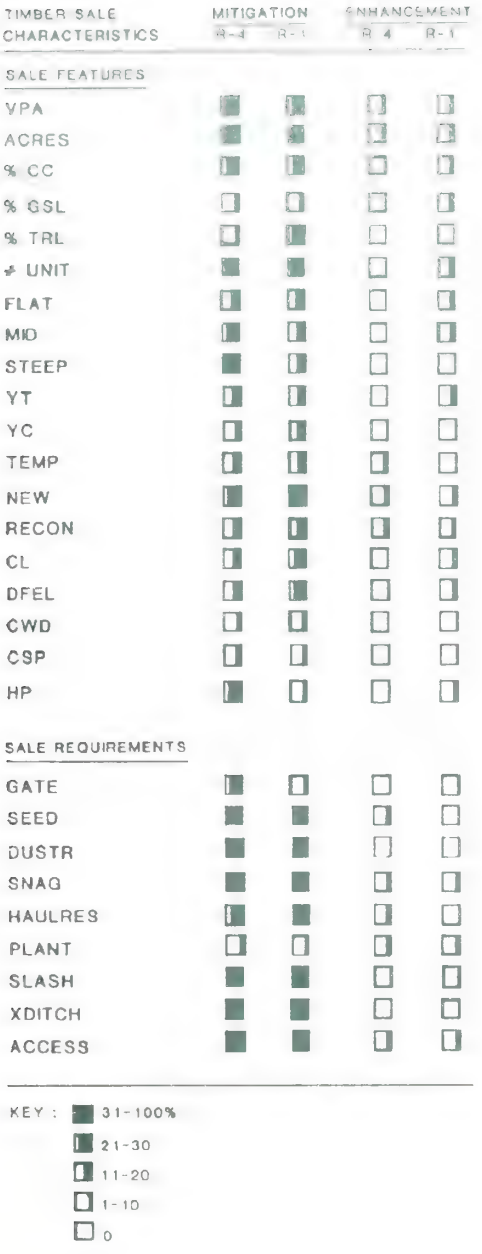

Figure 4—Percent modification for mitigation or enhancement purposes (R-4: Intermountain Region, R-1: Northern Region).

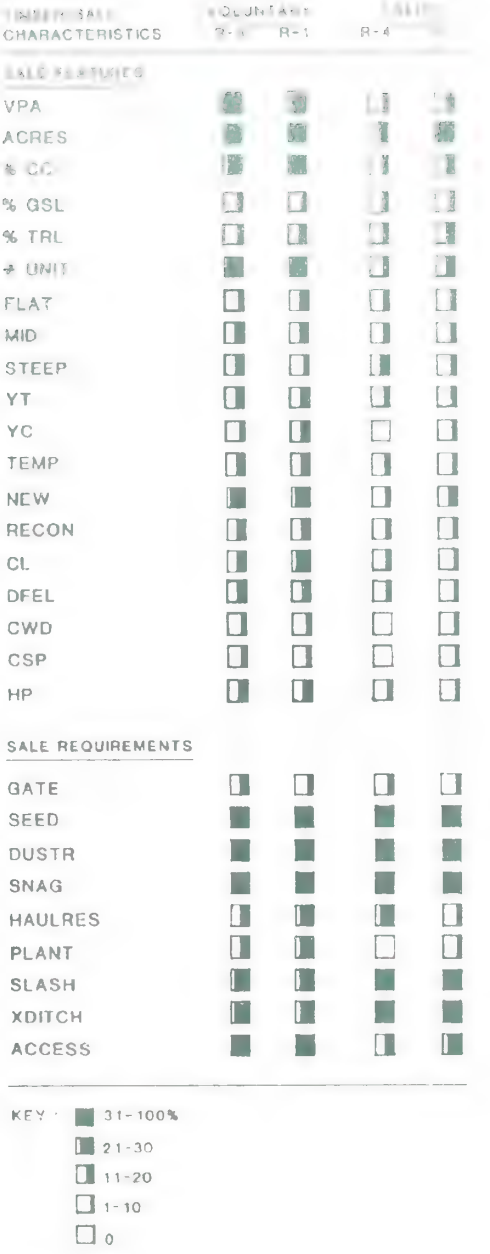

Figure 5—Percent modification for voluntary or policy-driven purposes (R-4: Intermountain Region, R-1: Northern Region).

requirements tend to be modified to a greater extent than are sale features. Sale requirements that are voluntarily modified on at least 31 percent of the timber sales include SEED, DUSTR, SNAG, and ACCESS. Only three of the 19 sale features are voluntarily modified on at least 31 percent of the timber sales in both Regions. These three sale features are VPA, ACRES, and #UNIT in the Intermountain Region, and ACRES, %CC, and #UNIT in the Northern Region.

When decision-making discretion is policy-based, sale requirements is the tool overwhelmingly chosen. SEED, DUSTR, SNAG, SLASH, and XDITCH are modified on at least 31 percent of the timber sales in the Intermount and Northern Regions. The most frequent response f the sale features is only in the range of 1 to 10 percen

Cost of Nontimber Provisions

The cost of the nontimber influence was estimated as the difference in stumpage value, expressed as statistical high bid (SHB), from a situation where all sale characteristics were set at their timber-only levels versus where they were set at the actual levels. This was done by modeling the residual value approach to stumpage appraisal using a system of equations.

Statistical Equations—From a statistical standpoint, the seemingly unrelated equations used to estimate the total dollars of SHB (see details in appendix tables 6 and 7) were quite satisfactory. The percentage of the variation explained by the equations (R^2) ranged from 30 (the transport equation) to 68 percent (the stump-to-truck equation) in the Intermountain Region and 13 (transport) to 78 percent (stump-to-truck) in the Northern Region. The equations contained a total of 22 different variables for the Northern Region and 24 for the Intermountain Region. Individual equations contained as few as two independent variables, as in the case of the equations for temporary roads, and as many as nine variables, as in the case of the Northern Region's stump-to-truck equation. (See Schuster and Niccolucci 1989a for presentation and illustration of similar equations.)

The cost equations for each appraisal phase and stumpage appraisal overbid were measured in terms of total dollars, not dollars per thousand board feet. This allowed changes in total dollars of costs and overbid to be viewed without the simultaneous influence of the changes in total volume harvested. For example, modifications, such as volume per acre harvested and acres harvested, change the cost of logging *and* the total volume harvested. Equations measured in total dollars allowed us to monitor changes in appraisal cost and total volume separately. Only at the final step of the analysis were the total dollars and total volume divided to estimate costs in dollars per thousand board feet.

Statistical High Bid—The cost of sale modifications for nontimber purposes used the statistical equations along with the timber-only and actual levels of the sale characteristics. Table 5 presents the estimated statistical high bids (SHB's) for the Intermountain and Northern Regions. The results indicate SHB's for the Intermountain Region would have been about $37/M bd ft for the timber-only timber sale design and $24/M bd ft for the actual design, for a difference of about $13/M bd ft. This difference amounts to approximately 54 percent of the actual SHB. The estimated revenue forgone for the nontimber influence in the Northern Region is more than $21/M bd ft, again about 54 percent of the actual SHB. In both Regions, stumpage value losses represent a 35 percent decrease from the timber-only SHB. Effects of base rate adjustment on SHB are reported in Schuster and Niccolucci (1989b).

Managerial Purpose—The majority of the costs were intended to mitigate adverse effects of the timber sale in the Intermountain and Northern Regions. The estimated costs of mitigation and enhancement were:

Managerial purpose	Intermountain Region	Northern Region
	1985 $/M bd ft	
Mitigation	11.55	16.36
About even	.09	2.98
Enhancement	1.31	2.12
Total	12.95	21.47

Approximately 76 percent of the costs in the Northern Region and 90 percent in the Intermountain Region were attributed to modifications intended to mitigate adverse effects of the timber sale. The remaining effect was accounted for by enhancement and the situation where mitigation and enhancement were about equally important.

Table 5—Statistical high bid and the cost of the nontimber influence

Sale design	Intermountain Region	Northern Region
	1985 $/M bd ft	
Timber-only	37.06	61.40
Actual	24.11	39.93
Difference	12.95	21.47

Managerial Discretion—The cost of managerial discretion was consistent between the Regions, as it was with managerial purpose. The estimated costs of managerial discretion for the Intermountain and Northern Regions were:

Managerial discretion	Intermountain Region	Northern Region
	1985 $/M bd ft	
Voluntary	2.37	8.73
Policy	10.58	12.74
Total	12.95	21.47

Policy-driven timber sale modifications accounted for 59 percent of the costs in the Northern Region; this compares to 82 percent of the costs in the Intermountain Region. Recall, figure 5 (presented earlier) showed most modifications were made voluntarily, but the costs portray a very different result. The explanation of this is as follows—timber sale modifications made voluntarily were less expensive than the required modifications.

MANAGEMENT IMPLICATIONS

The previous sections have highlighted the timber sale characteristic and how it was used to manage for the nontimber influence. The modification of the timber sale characteristic and its effect on stumpage price, the nontimber resource being managed, and the managerial motivation were addressed. Several of the findings have interesting management implications.

The land manager indicated that a majority of the timber sale characteristics were not modified for nontimber influences. But the statistical high bid in the Intermountain and Northern Regions was reduced by approximately 55 percent. This indicates that the modifications made, though few, were costly in terms of the reduction in statistical high bid. This may suggest that the manager needs to know not only the magnitude of modification, but also the corresponding effect on stumpage price as well.

A majority of the modifications were voluntarily motivated, according to the land manager. These voluntary changes account for about 18 and 41 percent of the reduction in statistical high bid in the Intermountain and Northern Regions, respectively. The voluntary nature of the modifications simply means the manager was not compelled by some policy requirement to implement

changes. If not required to modify the sale characteristic, did the benefits generated by the voluntarily modified sale characteristic equal or exceed the costs? Knowledge of the costs and benefits derived from voluntary actions will lead to sound economic decisions.

The factor analysis results showed timber sale modifications to be related to, and in certain cases providing for, the same nontimber influence. Understanding the linkages among sale characteristics will allow the land manager to produce more efficiently designed timber sales. Understanding the linkages will allow the land manager to efficiently account for the nontimber influence, and thus have the least impact on revenue returned to the treasury.

We estimated the cost of provisions for nontimber resources to be about $13 and $21/M bd ft in the Intermountain and Northern Regions, respectively, based on reduction in SHB. But this measure can be criticized because it was influenced partially by volume reductions. Some could argue that the volume is simply being shifted to the future. This is partially true, and this loss could be viewed as an opportunity cost of consuming in the future rather than the present. But some of the volume not harvested may never be available for harvest; trees left for wildlife escape routes or for streamside protection are examples. Also, the decrease in SHB may be attributed to sale design and layout. The sale design that considers the nontimber influence may not be efficient from a harvesting standpoint (Schuster and others 1984). If the sale design restricts the purchaser from harvesting the stumpage in the most efficient manner, the purchaser will decrease the bid price. This decrease in bid price cannot be captured in the future.

To this point we have considered the cost of the nontimber influence strictly as a percentage reduction in statistical high bid. There are other means of expressing this cost. For instance, nontimber influences represent almost 9 percent of the $149/M bd ft average logging cost in the Intermountain Region and about 8 percent of the $156/M bd ft average logging costs in the Northern Region. Similarly, in terms of the average final product value (log scale), the cost of the nontimber influence is approximately 3 percent in the Intermountain Region and 6 percent in the Northern Region.

Finally, throughout this paper the unit of measurement has been thousands of board feet, but acres is the unit of measurement used in land management. The cost of the nontimber influence from the standpoint of acres harvested is $133.13 per acre in the Intermountain Region and $437.34 per acre in the Northern Region. These represent about 9 percent of the $1,531 per acre of logging costs in the Intermountain Region and 14 percent of the $3,178 per acre logging costs in the Northern Region.

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APPENDIX: STUMPAGE VALUATION EQUATIONS

Table 6—Intermountain Region stumpage valuation equations

Equations	Coefficient	Standard error	R^2
Stump-to-truck			0.68
VPA	1,262.65	3,127.52	
ACRES	112.25	34.94	
%TRA	–4,552.40	860.39	
#UNIT	3,842.25	1,102.09	
STEEP	472.24	168.57	
YT	164.10	62.00	
DFEL	–1,023.14	360.59	
Constant	553,315.00	9,494.30	
Transport			.30
UHAUL	3,807.98	535.24	
PHAUL	3,282.25	535.40	
HAULRES	–33,178.30	18,306.50	
ACCESS	13,914.50	17,180.30	
DUSTR	8,670.38	22,207.00	
Constant	105,482.00	31,771.50	
Slash			.56
ADBH	–441.87	1,060.22	
VPA	–1,014.28	684.15	
ACRES	25.36	7.09	
%CC	360.51	102.03	
STEEP	59.25	30.66	
CSP	108.87	39.51	
#UNIT	667.66	215.11	
SNAG	11,578.20	6,907.69	
Constant	16,222.80	18,300.40	
Temp Road			.49
TEMP	3,273.00	333.82	
FLAT	–3.29	1.19	
Constant	3,990.50	934.30	
Spec Roads			.39
NEW	9,571.20	2,400.62	
RECON	7,604.36	2,494.03	
STEEP	268.64	54.50	
Constant	38,228.10	11,474.40	
Bid Premium			.31
SPLS	–.012	.008	
VPA	3,794.98	1,698.58	
YT	182.75	40.66	
CL	968.75	949.32	
PMETH	34,504.00	21,750.60	
SMETH	–20,631.40	29,803.20	
#BIDS	23,213.20	11,961.80	
Constant	–176,161.00	53,247.20	

Table 7—Northern Region stumpage valuation equations

Equations	Coefficient	Standard error	R^2
Stump-to-truck			0.78
VPA	18,266.50	1,650.36	
ACRES	1,211.28	121.71	
ADBH	–29,839.50	4,387.79	
%CC	–1,089.51	409.74	
YT	79.47	46.03	
#UNIT	4,424.47	1,750.45	
%GSL	2,260.60	1,179.02	
STEEP	538.70	188.92	
FLAT	–490.83	130.53	
Constant	111,181.00	75,474.00	
Transport			.13
UHAUL	4,384.44	760.84	
PHAUL	1,982.19	652.74	
ACCESS	9,998.45	22,370.60	
DUSTR	34,064.00	22,895.20	
Constant	101,084.00	35,254.70	
Slash			.48
ADBH	–4,601.96	1,437.35	
VPA	922.65	529.84	
ACRES	139.58	29.02	
%CC	136.07	132.44	
%GSL	–564.46	384.24	
FLAT	–130.39	31.50	
CSP	264.05	63.01	
#UNIT	2,294.25	583.31	
SNAG	–23,857.10	9,434.56	
Constant	68,969.70	25,079.80	
Temp Roads			.31
TEMP	3,684.93	481.98	
FLAT	–14.76	3.49	
Constant	5,164.12	1,239.49	
Spec Roads			.18
NEW	12,204.00	2,659.01	
RECON	5,652.78	3,158.11	
STEEP	23.65	74.22	
Constant	74,393.60	15,276.90	
Bid Premium			.49
SPLS	.07	.01	
ACRES	–213.34	91.73	
CL	2,939.23	1,387.02	
PMETH	–74,367.50	44,280.00	
#BIDS	61,234.20	9,700.30	
Constant	–140,550.00	69,759.50	

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Sale requirements were modified to accommodate nontimber concerns in a majority of the timber sales studied. Wildlife resources were the most frequent nontimber concern. The number of cutting units and total acres harvested were the sale features most often modified. Land managers indicated that mitigation was the dominant managerial purpose and that modifications were made voluntarily. Nontimber costs were estimated at $12.95 per thousand board feet in the Intermountain Region and $21.47 per thousand board feet in the Northern Region.

KEYWORDS: timber harvest, logging costs, system of equations, stumpage value

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Antiaggregative Effect of Verbenone on Response of the Mountain Pine Beetle to Baited Traps

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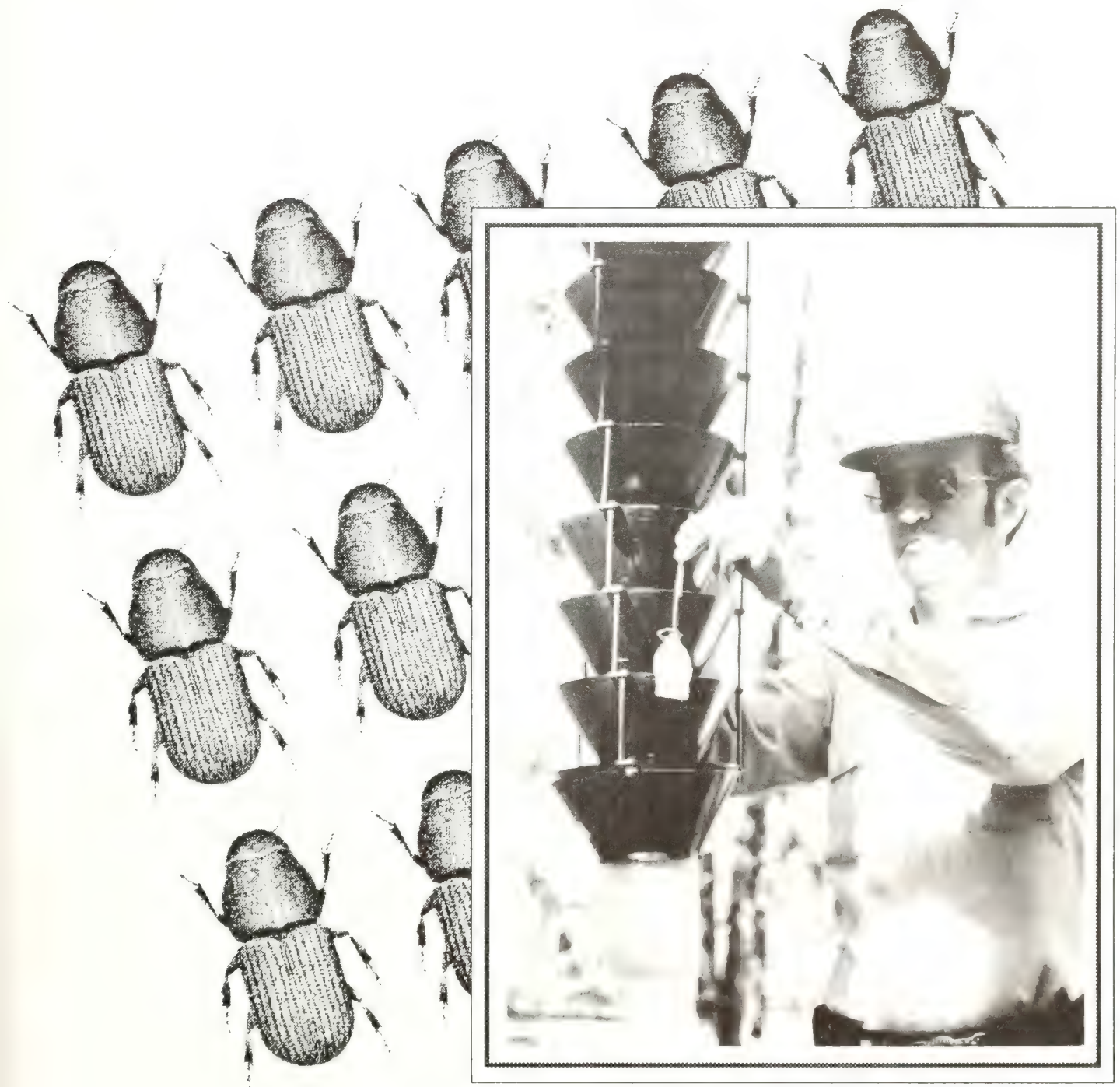

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RESEARCH SUMMARY

Response of the mountain pine beetle (MPB) (*Dendroctonus ponderosae* Hopkins) to Lindgren funnel traps baited with a commercial lure (*trans*-verbenol, *exo*-brevicomin, and myrcene), alone and in combination with verbenone, an aggregation-inhibiting pheromone, was measured in a lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) stand in Utah. Treatments tested were (1) single verbenone capsule alone, (2) single three-component MPB lure, (3) single three-component MPB lure and verbenone bubble cap, and (4) unbaited trap. Treatments were randomly assigned to four traps in each of eight test blocks. A total of 1,130 MPB were trapped during the flight period, with the greatest percentage (95.8) responding to the MPB bait alone. ANOVA revealed the numbers of MPB caught among treatments for the eight blocks combined were significantly different ($P < 0.001$). Tukey's Studentized Range Test revealed the treatments separated into two significantly different sets: (1) those three treatments for which fewest (4.2 percent) MPB were caught (verbenone, 0.6 percent; lure with verbenone, 1.7 percent; unbaited trap, 1.9 percent), and (2) that catching the greatest percentage (95.8 percent), the MPB lure alone. The lure alone, verbenone alone, and unbaited trap caught more females than males; respective sex ratios (males: females) were 0.57, 0.40, 0.50, while verbenone combined with the lure caught more males than females, sex ratio 2:1. Fisher's Exact Test revealed that treatment and response by sex were not independent, and when verbenone is added to the lure, more males than females will be caught.

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Antiaggregative Effect of Verbenone on Response of the Mountain Pine Beetle to Baited Traps

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INTRODUCTION

The chemical ecology of the mountain pine beetle (MPB) (*Dendroctonus ponderosae* Hopkins) like that of most other bark beetles, has proven to be especially difficult and costly to solve. The difficulty is due in large measure to the many compounds present in each of these semiochemical systems, the difficulty of isolating and identifying these chemical messengers, and the extensive field testing required to determine the behavioral response each elicits alone and in combination with the other components throughout a species' range. Components of these semiochemical systems and their effect on beetle behavior are yet to be determined (Lindgren and Borden 1989). As a result, most synthetic systems currently being tested do not elicit the same magnitude of beetle response as the natural systems (Lindgren and Borden 1989).

The advent of improved technology for isolating and identifying candidate compounds promises to speed total understanding of these semiochemical communication systems (Gries and others 1988). Until then, compounds that have been isolated and identified need to be field tested to determine the extent of variation in beetle response throughout its geographic range and under different test conditions—including a range in release rates, stand conditions, stand microclimate, and interactions with other pheromone and host tree components. The knowledge is needed to develop new strategies or to refine existing strategies (McGregor and others 1989) for manipulating localized populations. The intent is to integrate these strategies with existing silvicultural prescriptions (McGregor and others 1987) to prevent populations from reaching intolerable levels that require costly control. The purpose of the test reported here was to assess the antiaggregative effect of the (–) – enantiomer of verbenone when added to the standard commercial MPB lure, consisting of *exo*-brevicomin, *trans*-verbenol, and myrcene, on response of MPB populations in Utah. More specifically, we sought to determine if the anticipated reduction in MPB trapped would warrant further testing of verbenone for use in preventing MPB infestations in high-value stands, such as those in riparian zones, campgrounds, and critical big game habitat.

PRIOR RESEARCH

Discovery that bark beetles use a complex semiochemical communication system to attract and concentrate populations in sufficient numbers to overcome host resistance has led to efforts to exploit the system for bark beetle control (Anderson 1948; Chapman 1966; Wood 1962). Early efforts deployed attractive elements in a manner designed to lure flying beetles to lethal traps or to trees scheduled for harvesting (Pitman and Vité 1969). Unfortunately, beetle populations attracted to baited stands often "spilled over" into adjacent stands which the land manager intended to protect (Borden and others 1983; Rudinsky and others 1972). At the same time, efforts to isolate and identify the remaining major components of bark beetle pheromones revealed the presence of an antiaggregative element in the pheromones of several species, that, when deployed alone or in combination with the attractive elements, significantly reduced the number of beetles caught (Rudinsky and others 1972). A granular controlled-release formulation of MCH (3-methyl-2-cyclohexen-1-one), the antiaggregative element in the Douglas-fir beetle (DFB) (*D. pseudotsugae* Hopkins) pheromone, reduced infestations in windthrown trees (McGregor and others 1984).

Early isolation efforts revealed verbenone was a component of semiochemical systems of several species of *Dendroctonus*, and ensuing field tests showed it had antiaggregative properties (Renwick 1967). Renwick and Vité (1970) determined that the addition of verbenone to the attractive lure for the southern pine beetle (SPB) (*Dendroctonus frontalis* Zimmerman) reduced the number of males and females responding to traps, while Richerson and Payne (1979) found that a mixture of verbenone plus *exo*-brevicomin and *endo*-brevicomin reduced landing of SPB on unattacked trees, as well as reducing the density of emerging beetles on infested trees (Watterson and others 1982). But laboratory bioassays of SPB pheromones produced by beetles collected from three regions within its range have shown a significantly higher percentage of positive responses to pheromones produced by SPB from their respective regions, suggesting regional variation in their content (Berisford and Payne 1989). Similar geographic variation in pheromone composition and beetle response has been reported for the striped ambrosia beetle (*Trypodendron lineatum* Oliver) (Borden and others 1982) and the pine engraver beetle (*Ips pini* [Say]) (Lanier and others 1972; Miller and others 1989). Bedard and coworkers

(1980) found the addition of verbenone to the attractive lure reduced the catch of the western pine beetle (WPB) (*Dendroctonus brevicomis* Hopkins). Field tests utilizing verbenone 60:40 mix of (+) and (–) enantiomers released at four rates revealed that elution rates of 4.74 mg/24 h or greater reduced WPB catch at traps baited with its attractive lure by 92 percent or more (Tilden and Bedard 1988). Verbenone has also been shown to reduce response of *Dendroctonus adjunctus* (Blandford) to attractive bolts (Livingston and others 1983) and inhibit response of *Ips paraconfusus* (Lanier) (Byers and Wood 1981) and *Ips typographus* (L.) (Bakke 1981; Schlyter and others 1989). The first evidence that verbenone might function as an antiaggregant for the MPB resulted from laboratory and field bioassays that revealed (–) – verbenone inhibited response to selected semiochemicals (Ryker and Yandell 1983), although Pitman and collaborators (1969) were first to isolate trace amounts from the MPB. This isolation was later confirmed by Rudinsky and coworkers (1974).

In addition to its presence in the beetle, verbenone is produced by the auto-oxidation of *trans*-verbenol and *cis*-verbenol (Lindgren and Borden 1989), and there is also evidence for production of verbenone by oxidation of these compounds by yeasts commonly associated with the MPB (Hunt and Borden 1989). Lindgren and Borden (1989) have described the sequence of pheromone production for the MPB in lodgepole pine and the role of verbenone in generating an antiaggregative signal. This signal limits the density of beetle attack to a range that prevents overcrowding of the host tree.

Field tests in British Columbia to determine the antiaggregative activity of verbenone at two release rates (1.0 or 5.0 mg/24 h) revealed that verbenone significantly reduced male response to the commercial synthetic lure (*trans*-verbenol, *exo*-brevicomin, and myrcene) at both release rates, but not female response, although the reduction in female response approached significance (Borden and others 1987). Two large-scale field tests in Idaho (Amman and others 1989) and British Columbia (Lindgren and others 1989) that evaluated the effectiveness of verbenone for preventing attacks in susceptible lodgepole pine stands confirmed that verbenone has promise for manipulating local MPB populations.

STUDY DESCRIPTION

Test Location

The test was performed in a 110-year-old lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) stand, elevation 9,450 ft, approximately 8 miles south of Mountain View, WY, in the Wasatch National Forest. Stands within the test blocks were pure lodgepole pine, with exception of a few quaking aspen (*Populus tremuloides* Michx.). Average diameter breast height (d.b.h.) of lodgepole pines 5 inches and larger was 9.1 inches. The surrounding forest and the stands within the eight test blocks had been infested by MPB populations that had been building in numbers in previous years. The test blocks were located on a flat bench without intervening physiographic features that might alter air movement within or between blocks.

Test Design

The antiaggregative effect of verbenone was assessed in eight blocks 100 ft square. The blocks were arranged in two rows of four, with the rows oriented in an east-west direction and a separation of 100 ft between blocks (fig. 1). The 16-unit Lindgren multiple funnel traps (Lindgren 1983) were positioned at 100-ft intervals, at the corners of each block (fig. 2). Traps were suspended by nylon cord from tree limbs so that they could be lowered to collect the beetles that were caught. A standard trap height was obtained by positioning the plastic containment device at the base of the funnels, 6 ft above ground. Traps were suspended from nonhost trees, old dead lodgepole pines, or lodgepole pines with diameters less than 5 inches (breast height) to minimize the possibility that responding MPB might infest trees on which traps were hung and thereby alter the composition of the assigned treatment.

The four treatments tested were (1) single verbenone bubble cap alone (fig. 2); (2) single three-component MPB tree bait alone (fig. 3); (3) single verbenone bubble cap and a three-component MPB lure; and (4) unbaited trap. The treatment components were suspended in the funnel openings from wire hangers clipped to the lip of the funnels in the order shown in fig. 3. Verbenone bubble caps were suspended from the hangers in the same manner and position as that for the *trans*-verbenol bubble caps. Release rates and devices for each semiochemical treatment are shown in table 1.

Treatments were randomly assigned to the four traps in each block. Traps were in place and baited 2 weeks prior to the onset of beetle flight. Collections were made weekly thereafter, and the insects caught were placed in 70 percent alcohol and taken to the laboratory for specific determination.

RESULTS AND DISCUSSION

A total of 1,130 MPB were trapped in the eight blocks, with the greatest percentage (95.8) responding to the MPB bait alone (table 2). Analysis of variance revealed the total numbers of MPB caught among treatments for the eight blocks combined were significantly different ($P < 0.001$). Tukey's Studentized Range Test showed the treatments separated into two sets (table 2). The treatments for which the fewest MPB were caught included the MPB lure with verbenone (1.7 percent), verbenone alone (0.6 percent), and the unbaited trap (1.9 percent). These three treatments accounted for only 4.2 percent of the MPB trapped. The MPB lure alone, which accounted for 95.8 percent of the MPB trapped, comprised the second set that differed significantly from the first set. The results show that the addition of – (–) verbenone significantly reduces the number of MPB responding to the synthetic lure. Comparison of MPB response to the four treatments among the eight blocks revealed that the variation in the percentage of MPB caught by treatment was minimal (fig. 4). The single exception was recorded in block eight, where the percentage caught in the unbaited trap was slightly higher than in the remaining seven blocks, despite the fact fewer beetles were trapped in this block than any other block. This trap was positioned in the extreme southwest corner of the test

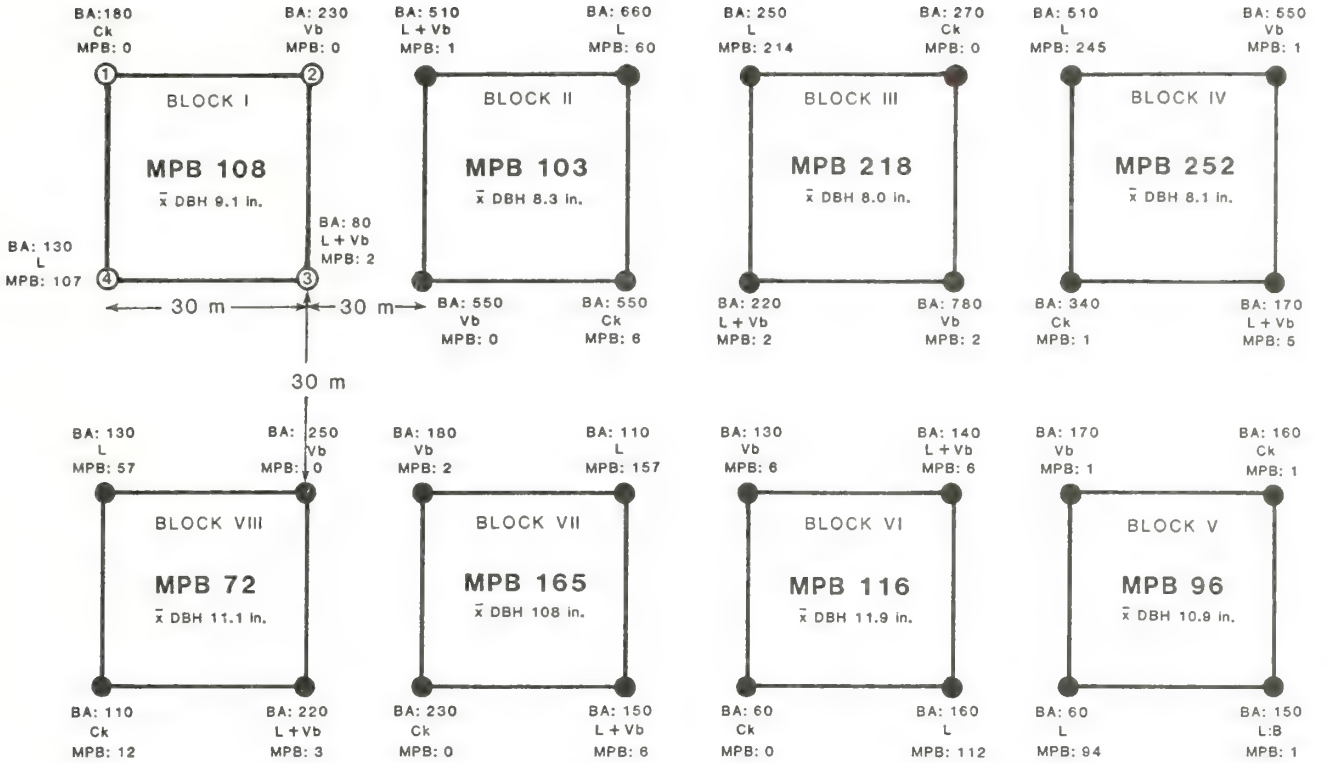

Figure 1—Test block alignment, including mean lodgepole pine diameter (breast height) and MPB trapped per block, as well as basal area (BA), treatment assignments (L = lure, Vb = verbenone, Ck = unbaited trap), and MPB caught (MPB), by trap position within each block.

Figure 2—Lindgren funnel trap showing plastic container at funnel base that retains beetles caught, and wire hanger with bubble cap that is suspended within funnel opening by clipping hanger over the edge of the funnel.

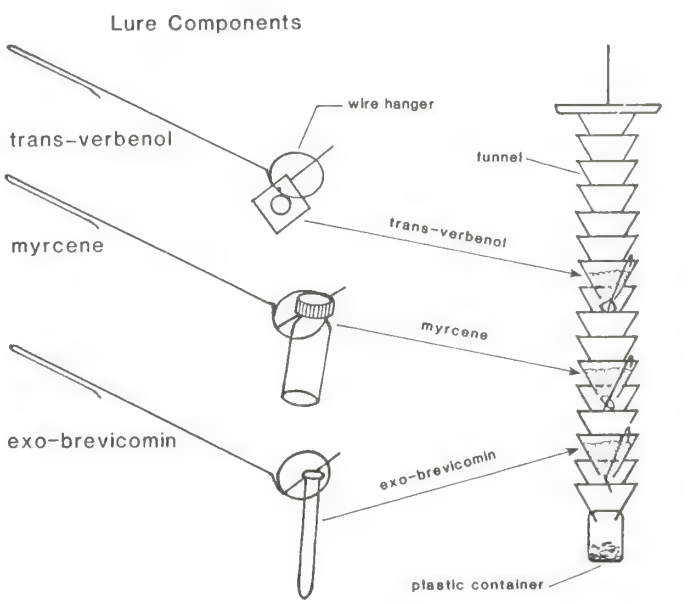

Figure 3—Positions of release devices used to dispense the three-component mountain pine beetle lure and verbenone on the 16-unit funnel traps. *Trans*-verbenol and verbenone were released from polyethylene bubble caps, myrcene from a closed 20-mL polyethylene bottle, and *exo*-brevicomin from a glass capillary tube within an open polyethylene centrifuge tube.

Table 1—Semiochemical release devices and rates

Compound[1]	Release device	Release rate[2]
Verbenone	Polyethylene bubble cap	5.0
MPB lure (three components):		
trans-verbenol	Polyethylene bubble cap	2.0
exo-brevicomin	Glass capillary tube (1.0 mm i.d.) in open 400-µL polyethylene centrufuge tube	.2
myrcene	Closed 20-mL polyethylene bottle	17.6

[1]Chemical names, supplier and purity of semiochemicals tested:
1. Verbenone: 4,6,6-trimethylbicyclo [3.1.1] hept-3-en-one; Phero Tech Inc., Vancouver, BC; 98.2% pure.
2. *trans*-verbenol: trans-4,6,4-trimethylbicyclo [3.1.1] hept-3-en-2-ol; Phero Tech Inc., Vancouver, BC; 93.6% pure.
3. *exo*-brevicomin: exo-7-ethyl-5-methyl-6,8-dioxabicyclo [3.2.1] 1, octane; Phero Tech Inc., Vancouver, BC; 99.7% pure.
4. Myrcene: 2-methyl-6-methylene-octa-2,7 diene; Phero Tech Inc., Vancouver, BC; 98% pure.

[2]Release rate = mg/24 h at 25 °C.

area, and because pevailing winds were from the south-southwest, it is unlikely that the catch was affected by treatments present in adjacent traps (fig. 3).

The reduction (95.8 percent) in MPB response to the current commercial attractive lure in the presence of verbenone in this test was greater than that recorded by others. Ryker and Yandell (1983), working in eastern Oregon, reported an 86 percent reduction in MPB response after a 9-day-long test, when verbenone (91.4 percent (–) at 1,000 ppm) was added to an MPB lure (*trans*-verbenol, 20 mg/h; 1:1 mixture of myrcene and alpha pinene at 600 mg; plus an additional vial of alpha pinene at 1 to 2 mg/h). In British Columbia, Borden and collaborators (1987) recorded a reduction of approximately 65 percent in the mean number of beetles trapped over a 3-day period when (–) verbenone (5.0 mg/24 h) was added to the MPB lure (myrcene 8 mg/24 h, *trans*-verbenol 1.0 mg/24 h, *exo*-brevicomin 0.1 mg/h).

Differences in test methodology among the three tests, including use of different lure components, release rates of test components, and test durations, preclude any inference about inherent differences in response among the Oregon, British Columbia, and Utah MPB populations.

Of the 1,130 MPB trapped, 410 were males and 720 were females (sex ratio 0.56) (table 2). The lure alone, verbenone alone, and unbaited trap caught more females than males; respective sex ratios (males:females) were 0.57, 0.40, and 0.50 (table 2). In contrast, the lure with verbenone caught more males than females, resulting in a sex ratio of 2.1. A contingency table analysis using Fisher's Exact Test (2-Tail) was used to test for independence between treatment and response by sex (table 3). The analysis revealed

Table 2—Response of the mountain pine beetle to funnel traps baited with synthetic MPB lure and verbenone, alone and in combination, Wasatch National Forest, UT, 1986

Block	Average d.b.h. LPP	MPB lure alone			MPB lure with verbenone			Verbenone alone			Unbaited trap			Total		
		Females	Males	Total	Females	Males	Total	Females	Males	Total	Females	Males	Total	Females	Males	Combined
	Inches	*Number*														
1	9.1	77	30	107										77	31	108
2	8.3	58	38	96		1	1				4	2	6	62	41	103
3	8.0	130	84	214	1	1	2	2		2				133	85	218
4	8.1	171	74	245	1	4	5	1		1		1	1	173	79	252
5	10.9	66	28	94		1	1	1		1				67	29	96
6	11.9	68	44	112		1	1		1	1	2		2	70	46	116
7	10.8	89	68	157	3	3	6	1	1	2				93	72	165
8	11.1	36	21	57	1	2	3				8	4	12	45	27	72
Total		695	397	1,082	6	13	19	5	2	7	14	8	22	720	240	1,130
Percent		64	36	95.8	32	68	1.7	71	29	0.6	75	25	1.9			
Sex ratio (males:females)		0.57				2.1			0.40			0.50				
Mean		[1]11.433*a*				1.759*b*			1.333*b*			1.726*b*				

[1]Means with the same letter are not significantly different ($P < 0.001$).

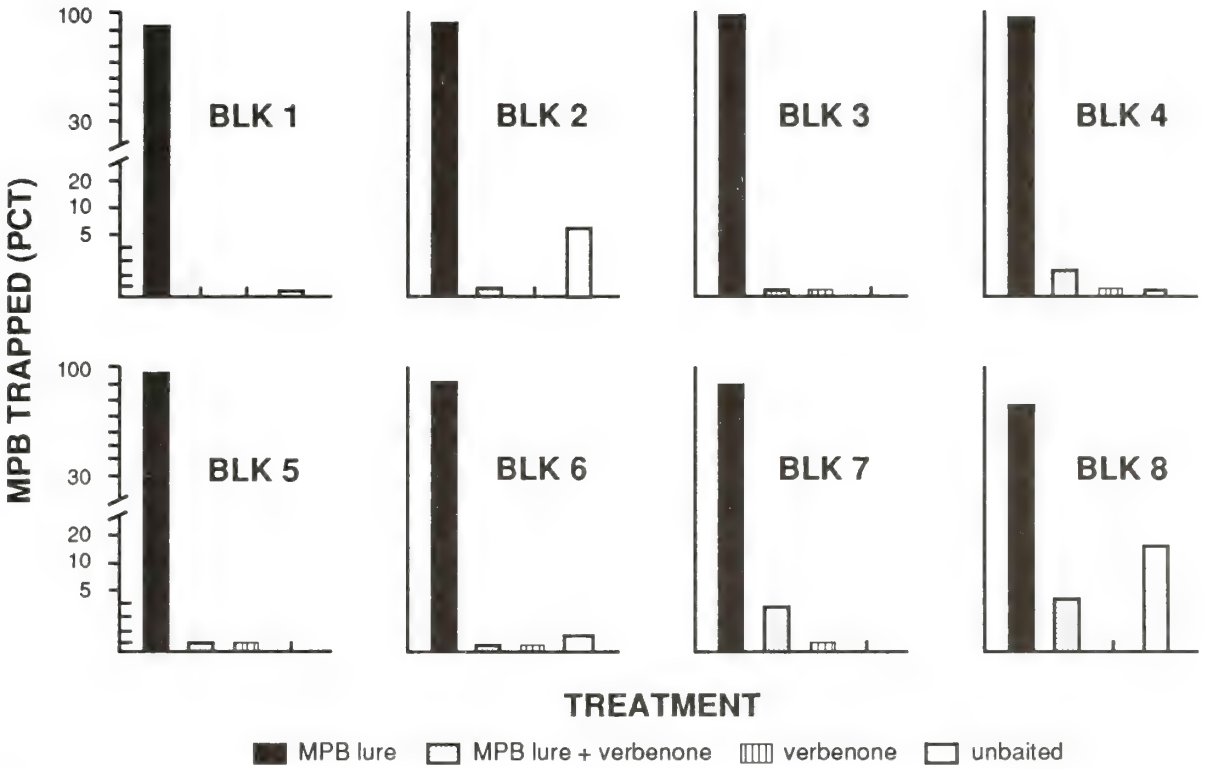

Figure 4—Percentage of mountain pine beetles trapped, by treatment, for the eight test blocks, Wasatch National Forest, UT, 1986.

Table 3—Contingency table comparing mountain pine beetle response, by sex, to the lure alone, lure with verbenone, verbenone alone, and unbaited trap[1]

Treatment	Sex		Total	
	Males	Females		
			No.	*Percent*
Lure alone				
Number	387	695	1,082	95.75
Percent	34.25	61.50		
Row percent	35.77	64.23		
Column percent	94.39	96.53		
Lure + verbenone				
Number	13	6	19	1.68
Percent	1.15	0.53		
Row percent	68.42	31.58		
Column percent	3.17	.83		
Verbenone alone				
Number	2	5	7	0.62
Percent	0.18	.44		
Row percent	28.57	71.43		
Column percent	.49	.69		
Unbaited trap				
Number	8	14	22	1.95
Percent	.71	1.24		
Row percent	36.36	63.64		
Column percent	1.95	1.94		
Totals				
Number	410	720	1,130	
Percent	36.28	63.72		100.00

[1]Fisher's Exact Test (2-Tail) value = 0.0336.

that treatment and response by sex are not independent, and when verbenone is added to the lure we can expect more males than females to be trapped.

Given the current understanding of MPB response to verbenone, the reason for the change in sex ratio of MPB responding to treatment (lure with verbenone compared to the lure alone, verbenone alone, and the unbaited trap) is unclear. The number of females responding to the lure with verbenone, and verbenone alone, was almost identical; however, the number of males responding to the lure with verbenone was six times greater. Results from a short-term initial field test in British Columbia revealed a proportional reduction in male and female response when verbenone was added to the lure (Borden and others 1987). Recent electroantennogram (EAG) measures of MPB response to racemic pheromone components revealed recovery rates following exposure to the three-component lure and verbenone were longer for males than females (Whitehead 1986). Recovery rates are thought to be affected by the amount of time a stimulant molecule is bound to a membrane receptor (Roelofs and Comeau 1971). Further, such sex-related differences in response may be the result of a different number or type of antennal receptor. Electroantennogram analyses have also determined the calculated threshold of response to verbenone was higher for males than females, while response to the three-component lure was almost identical (Whitehead and others 1989). The change in sex ratio among treatments could result from a synergistic effect triggered by the addition of verbenone and augmented by the auto-oxidation of the *trans*-verbenol in the lure to verbenone. It has been suggested that the effect of such a reaction may be to stimulate separate sensory cells in the antenna or occupy multiple receptor sites on single sensory cell membranes resulting in a differential response (Whitehead 1986). The effect may differ by sex because of differences in the number or type of receptors common to each sex.

CONCLUSIONS

Results from this test suggest that verbenone, when deployed prior to beetle flight, offers considerable promise for interfering with the aggregation behavior of MPB populations and preventing them from reaching unacceptable levels, especially in high-value stands. The fate of beetles deterred from aggregating on suitable host in the presence of verbenone is unknown. Accordingly, at this stage of development its potential for reducing intolerable levels of infestation would likely be enhanced if it were deployed in conjunction with synthetic MPB lures to attract beetles avoiding the area treated with verbenone. The lures could be deployed in lethal traps or less valuable stands that could be treated to destroy any residual infestations. The test results showed that of 1,130 MPB trapped, 1,101 (97.5 percent) responded to traps baited with the attractive lure. If the 1,130 MPB trapped represented the total MPB population in the test area, only 29 (2.5 percent) remained free to infest suitable trees (table 2). A sensible alternative would be to invoke such a strategy when MPB populations are at low or endemic levels, so that the effort required to trap-out or treat residual populations is more managable. This alternative requires knowledge of the dynamics of endemic populations so that stands likely to harbor such infestations can be identified and treated in a timely manner. Such strategies will also require continued field testing of verbenone to assess the effectiveness of current elution rates against different MPB population levels throughout the range of LPP and other host species because of potential host, and geographic differences (see Lanier and others 1980). Efforts to gain this level of understanding are part of the Intermountain Research Station's program to devise strategies for preventing MPB populations from building to unacceptable levels.

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Mountain pine beetle (MPB) (*Dendroctonus ponderosae*) response to Lindgren funnel traps baited with a commercial lure (*trans*-verbenol, *exo*-brevicomin, and myrcene), alone and in combination with verbenone, an aggregation-inhibiting pheromone, was measured in a lodgepole pine (*Pinus contorta*) stand in Utah. Treatments were randomly assigned to four traps in each of eight test blocks. A total of 1,130 MPB were trapped during the flight period. ANOVA revealed the number of MPB caught among treatments was significantly different ($P < 0.001$). Tukey's studentized range test revealed MPB caught among treatments separated into two significantly different sets: (1) verbenone (0.6 percent), lure with verbenone (1.7 percent), unbaited trap (1.9 percent); and (2) the MPB lure alone (95.8 percent).

KEYWORDS: *Dendroctonus ponderosae*, Scolytidae, pheromones, *Pinus contorta*

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Relationship of Fuel Size and Spacing to Combustion Characteristics of Laboratory Fuel Cribs

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RESEARCH SUMMARY

Flaming combustion in cribs of large woody fuels, thickness 5 cm or greater, is not sustained when fuel spacing ratio, fuel edge-to-edge separation distance to fuel thickness, is greater than 3:1. The burning rate per unit of exposed fuel surface area was found to reach a maximum near a porosity of 0.21, where porosity is defined as the square root of the ratio of vertical venting area to the exposed large fuel surface area. The flame length associated with the large-fuel burning rate was found to drop rapidly when the porosity exceeds 0.3 and the large-fuel spacing ratio increases beyond 2.23:1. This supports the critical spacing assigned in the large fuel subroutine burnout of Albini's (1976b) fire modeling program.

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Relationship of Fuel Size and Spacing to Combustion Characteristics of Laboratory Fuel Cribs

Hal E. Anderson

INTRODUCTION

Study of fire behavior in wildland fuels has concentrated on the dependence of the rate of spread on fuel properties, fuel moisture contents, slope, and wind (Rothermel 1972). As the knowledge base developed and use of mathematical models became more common, users expressed interest in other aspects of fire behavior. These interests included areal fire growth and size, flame length and tree crown scorch, energy release rates, and spotting distances, including fire duration and burnout properties (Albini 1976a, 1976b). A model of the mass loss history of fuels was developed by Albini that provides an estimate of the duration of flaming combustion and the fire intensity of wildland fires. The model is limited to fuel consumption during the flaming phase of the burning process. The model included an estimate of the planform fuel separation distance (2.33:1) at which a specific fuel size can no longer sustain flaming combustion in adjacent fuels.

Since several assumptions used in Albini's model have not been tested, a study was undertaken to determine the accuracy of the assumption of fuel spacing and provide additional insights into the burning rates during flaming. This paper presents results showing the dependence of the burning rate and flame length on the physical properties of square cribs of large-sized woody fuels. Fuels included square sticks, either 5.08 cm (2.0 in), 10.16 cm (4.0 in), or 15.24 cm (6.0 in) in thickness and 122 cm (4.0 ft) in length. The spacing of fuels varied from 0.5 to 3.0 times the thickness of the large fuel. Smaller fuels were used to ignite the crib and provided a measure of how the burning rate tracked combustion of each size class. Results confirm that the burning rate was affected by porosity and spacing. The variation in the burnout of fuel sizes between the burnout model and observation shows how the flaming phase changes with fuel size and spacing. The influence of moisture content was considered by burning a few cribs at about 12 percent and 20 percent moisture content. Flame length showed a sharp drop as spacing was increased and porosity became more open.

PRIOR RESEARCH

The burning of wood cribs for both spreading fires and nonspreading or area fires has been investigated for years to develop an understanding of fire behavior. Harmathy (1972a, 1972b) presented an extensive review of previous work on crib fires within enclosures and in unconfined atmospheres. That work, plus the research of others, provided a basis for evaluating certain aspects of the burnout model developed by Albini (1976b), such as investigating the effect of spacing on the flaming burnout (Block 1971; Gross 1962; Heskestad 1973; Smith and Thomas 1970; Thomas 1974). These authors pointed out that the burning rates of wood crib area fires fell into two regimes: (1) when the fuels are closely packed, the burning rate is ventilation controlled, and (2) when the fuels are quite loosely packed, the burning rate is controlled by the exposed fuel surface area. The general form has been presented by several researchers (Block 1971; Delichatsios 1976; Gross 1962; Harmathy 1972a, 1976; Heskestad 1973), but has been expressed differently because of scaling factors or because dimensionless analysis functions were used to group the variables. Smith and Thomas (1970) expressed similar observations noting a decrease in the burning rate with large spacing. This suggested that burnout of large fuels could be expressed in terms of, or a function of, the porosity. Comments following Block's paper (1971) at the 13th symposium on combustion brought out this concept in response to A. M. Kanury. Block (1971) expressed the thought that, at extremely open conditions, the burning rate would start to decrease and a series of negative sloped lines for each size would describe the dependence on porosity. Heskestad (1973) noted in his paper that the ventilation controlled curve rising toward the "constant" burning rate portion is a section of a parabola. This suggests that Block's thought about decreased burning rates in open fuel beds could be represented by a parabolic response function that covers the rising burn rate at small ventilation or porosity values and the decreasing burn rate at large ventilation or porosity values. Research on fire spread in wildland fuels for horizontal or vertical rates of spread has indicated that mass loss rates reach a maximum at a critical bulk density or packing ratio and then decline with further changes in the bulk density (Frandsen and Schuette 1978; Rothermel 1972; Wilson 1982).

Review of the above research indicated that, in both the ventilation-controlled and the surface-area-controlled regions, the mass loss rate per unit area of exposed fuel surface is basically a function of the ratio of ventilation area to exposed fuel surface area to the one-half power.

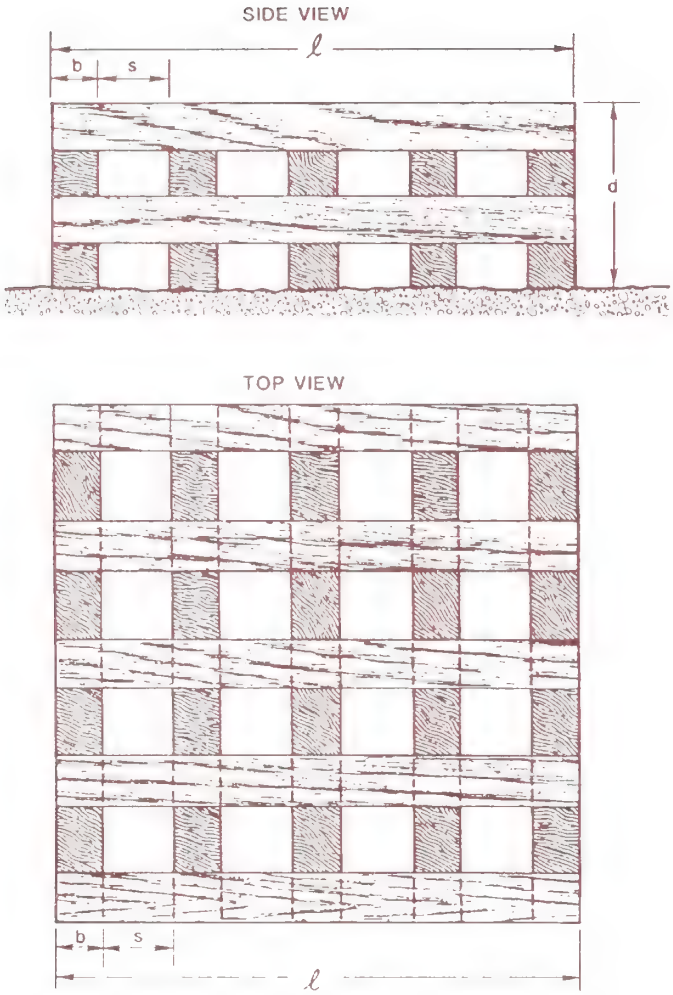


Figure 1—General configuration of large fuel in wood crib used to study the flaming burnout properties of fires. Thickness is denoted by *b*, spacing of pieces by *s*, length of pieces by ℓ, and depth of the fuel bed by *d*.

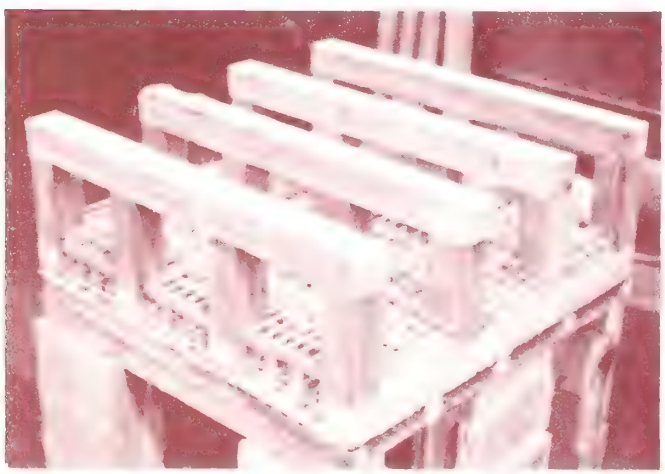


Figure 2—An oblique view of a fuel bed being constructed. Shows the arrangement of fine fuels between the large fuels and the horizontal and vertical spacing of the large fuels.

This ratio is a major term known as the porosity factor (Gross 1962; Heskestad 1973), and can be expressed mathematically as:

$$R_r/A_s = f(A_v/A_s) \quad (1)$$

where R_r = mass loss rate per unit area of fuel surface, g/s
A_s = area of exposed fuel surface, cm²
A_v = cross-section area of vertical vents in the crib, that is, the planform area not occupied by fuel, cm².

This relation provides a basis for evaluating how burning rate changes as the fuel bed becomes more and more open.

The exposed surface area of the large fuels was determined from the total surface area by subtracting from it the surface area of the perimeter outward-facing sides of the pieces, the surface area of the top and bottom layers' outward-facing sides, and the surface areas that are covered at each intersection of the pieces. These outward-facing and shielded surface areas were subtracted from the total surface area because they do not interact with the fire in the fuel arrangement. The general geometry is shown in figure 1 for a fuel bed where the spacing is only horizontal. When vertical spacing equal to the horizontal spacing is desired, large fuel pieces equal to the spacing distance in length are used to separate each layer of large fuels (fig. 2). For horizontal spacing the equation for the exposed surface area is:

$$A_{sh} = 2N(n-1)b\ell + 2(N-1)n(b\ell^2 - nb^2) \quad (2)$$

where b = fuel stick thickness, cm
ℓ = fuel stick length, cm, also fuel bed width
n = number of sticks per layer
N = number of layers.

When vertical spacing is added, the equation for the additional exposed surface area is:

$$A_{sv} = 4bsn(n-1)(N-1) \quad (3)$$

where s = the spacing distance, cm, and the length of support pieces of the large fuel.

The vertical venting area was determined from the spacing and the number of pieces:

$$A_v = (n-1)^2 s^2 \text{ cm}^2 \quad (4)$$

This paper reports on the relationship of the burning rate to changes in the fuel stick size, spacing, and resulting fuel bed porosity.

EXPERIMENTAL PROCEDURES

The experiments were conducted using squared sticks positioned at specific distances from one another in square cribs that had a maximum base of 122 cm (4.0 ft) on a side. Fuel sizes included starter fuels used to bring the large fuels into combustion in a manner similar to the burning process observed in the field. These fuels included 0.07-cm (0.027-in)-thick excelsior of aspen wood (*Populus tremuloides* Michx.), 0.635-cm (0.25-in) and 2.54-cm (1.0-in) sticks of ponderosa pine (*Pinus ponderosa* Laws.), or sugar pine (*Pinus lambertiana* Dougl.).

Larger fuels were one of the following sizes: 5.08-cm (2.0-in), 10.16-cm (4.0-in), and 15.24-cm (6.0-in) square sticks of ponderosa pine, Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), or lodgepole pine (*Pinus contorta* Dougl.); or a mixture of Engelmann spruce (*Picea engelmannii* Parry) and subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.). The fuels in a majority of the experimental burns were conditioned to 6 percent moisture content (mc) ovendry (OD). A few of the burns, however, had the large fuels conditioned at 11 to 14 percent mc OD and 20 to 22 percent mc OD. An initial series of burns was carried out to determine the burnout characteristics of the 2.54-cm (1-in) fuels because their burnout would be considered a reference for the burning rate of the larger fuels. Spacing of the 2.54-cm (1-in) fuels was varied vertically and horizontally to establish how the small fuels would be distributed. As a result the 0.63-cm (1/4-in) sticks were spaced at a spacing ratio, spacing distance to fuel thickness, of 8:1 and the 1-inch sticks at a ratio of 5:1 for all the burns. For the larger fuels the spacing was varied from a low ratio of 0.5:1 to a high ratio of 3:1. Physical properties of the fuel beds are presented in table 1, and each burn is identified by a sequence of properties: species; thickness (*b*); spacing ratio (*sr*); number of pieces per layer (*n*); number of layers (*N*); horizontal, *H*, or horizontal and vertical, *HV*, spacing; and percent mc.

Table 1—Identification of each test fire by species, thickness (*b*), spacing ratio (*sr*), number of pieces per layer (*n*), number of layers (*N*), piece orientation (H or HV), moisture content (mc), and physical properties of each crib

Item	Species	Thickness *b*	Spacing ratio *sr*	No. per layers *n*	No. of layers *N*	Type of spacing	Moisture content mc	Stick length ℓ	Crib depth *d*	Total weight Wt	Large fuel weight Wl
		cm					*Percent*	----- *cm* ----		----- *kg* -----	
1	DF	5.08	1.00	12	4	H	6.0	116.0	20.3	78.30	70.30
2	PP	5.08	1.00	12	4	H	6.0	116.0	20.3	61.40	53.20
3	LP	5.08	1.50	10	4	H	6.0	119.0	20.3	51.20	43.00
4	SF	5.08	2.23	8	4	H	6.0	121.0	20.3	45.70	36.80
5	DF	5.08	2.23	8	4	H	6.0	121.0	20.3	57.30	46.20
6	LP	5.08	2.23	8	4	H	6.0	121.0	20.3	44.10	35.40
7	PP	5.08	2.23	8	4	H	6.0	121.0	20.3	46.30	37.20
8	PP	5.08	3.00	6	4	H	6.0	106.0	20.3	32.00	24.80
9	SF	10.16	.50	8	4	H	6.0	116.0	40.6	160.00	146.00
10	LP	10.16	1.50	5	4	H	6.0	111.0	40.6	98.80	83.30
11	PP	10.16	1.50	5	4	H	6.0	111.0	40.6	102.00	88.70
12	SF	10.16	2.00	4	4	H	6.0	101.0	40.6	72.30	58.70
13	DF	10.16	2.50	4	4	H	6.0	116.0	40.6	105.00	86.50
14	LP	10.16	2.50	4	4	H	6.0	116.0	40.6	88.00	71.10
15	PP	10.16	2.50	4	4	H	6.0	116.0	40.6	93.00	77.80
16	PP	15.24	.67	5	4	H	6.0	116.0	60.9	217.00	198.00
17	PP	15.24	1.00	4	4	H	6.0	106.0	60.9	164.00	147.00
18	PP	15.24	2.50	3	3	H	8.0	121.0	45.7	106.00	90.70
19	PP	15.24	2.50	3	4	H	8.0	121.0	60.9	161.00	138.00
20	SF	5.08	.50	16	4	H	11.5	119.0	20.3	81.90	73.40
21	LP	5.08	.50	16	4	H	22.0	119.0	20.3	95.90	85.70
22	DF	5.08	3.00	6	4	H	20.4	106.0	20.3	41.90	32.10
23	PP	5.08	2.50	7	4	H	20.0	111.0	20.3	39.50	31.30
24	DF	10.16	1.00	6	4	H	13.7	111.0	40.6	152.00	135.00
25	DF	10.16	1.00	6	4	H	22.0	111.0	40.6	152.00	135.00
26	LP	10.16	2.50	4	4	H	20.0	116.0	40.6	102.00	85.70
27	SF	15.24	2.50	3	4	H	20.0	121.0	60.9	170.00	146.00
28	PP	5.08	1.00	12	4	HV	6.0	121.0	35.5	81.10	64.80
29	PP	5.08	1.50	10	3	HV	6.0	121.0	33.0	78.30	50.30
30	PP	10.16	1.00	7	4	HV	6.0	121.0	71.1	188.00	163.00
31	PP	10.16	2.50	4	3	HV	6.0	121.0	83.8	159.00	94.60
32	PP	15.24	.75	5	3	HV	6.0	121.0	71.1	235.00	209.00
33	PP	15.24	1.50	4	3	HV	6.0	121.0	93.9	199.00	170.00
					Data Used From Gross						
34	DF	1.90	.50	7	10	H	9.2	19.0	19.0	2.11	2.11
35	DF	1.90	1.25	5	10	H	9.2	19.0	19.0	1.53	1.53
36	DF	1.90	3.50	3	10	H	9.2	19.0	19.0	.91	.91
37	DF	1.90	.50	7	7	H	9.2	19.0	13.3	1.49	1.49
38	DF	1.90	1.25	5	7	H	9.2	19.0	13.3	1.06	1.06
39	DF	1.90	3.50	3	7	H	9.2	19.0	13.3	.64	.64
40	DF	1.90	.50	7	5	H	9.2	19.0	9.5	1.05	1.05
41	DF	1.90	1.25	5	5	H	9.2	19.0	9.5	.75	.75
42	DF	1.90	.50	7	3	H	9.2	19.0	5.7	.65	.65
43	DF	1.90	1.25	5	3	H	9.2	19.0	5.7	.45	.45
44	DF	2.54	.50	7	10	H	9.2	25.4	25.4	5.97	5.97
45	DF	2.54	1.25	5	10	H	9.2	25.4	25.4	4.15	4.15
46	DF	2.54	3.50	3	10	H	9.2	25.4	25.4	2.57	2.57
47	DF	3.81	.50	7	10	H	9.2	38.1	38.1	18.60	18.60
48	DF	3.81	1.25	5	10	H	9.2	38.1	38.1	13.50	13.50
49	DF	9.15	.29	8	10	H	9.2	91.5	91.5	315.00	315.00
50	DF	9.15	.50	7	10	H	9.2	91.5	91.5	262.00	262.00

Weight loss per unit time was measured with a four-station load cell/strain gauge instrumentation setup that included heat isolation materials, a support platform, and the fuel bed. Flame height (fig. 3) was observed by three individuals making independent measurements, which were recorded on small cassette tape recorders. These observations were later coordinated and the average flame height over time included as part of the data base. In addition, two remote-controlled cameras recorded flame height at specific time intervals as set up within a microcomputer/controller. Radiant heat signatures for each fire were measured with radiometers located (1) at right angles to the flame plume, at the fuel bed height above the combustion laboratory floor; (2) at a height of 493 cm (16 ft 2 in) above the combustion laboratory floor, and 503 cm (16 ft 6 in) from the center line of the fuel bed on a line-of-sight angle of 40 degrees from the horizontal. The temperature in the base of the fuel bed was estimated with a chromel-alumel thermocouple placed approximately 30.48 cm (1.0 ft) into the fuel bed. The temperature of a load cell was monitored so correction could be made for thermal drift of the weight loss millivolt signal. All of the sensor electronic signals were collected and stored on a compact data collection unit, and after each burn the data were stored on tape and later included in a data base.

The individual observers were instructed to note each significant change that occurred during the burnout of the fuel bed. The time of each event was recorded on the tape recorders. The three observers were utilized through the flaming phase, which generally did not exceed 60 minutes. During the charring or glowing phase, one individual made observations until the fuel had totally burned out, leaving less than 5 percent of the area covered with embers. Among the significant observations were: the collapse and burnout of each of the starter fuel sizes, flame height at each observation, buildup of burning in the fuel bed, the fraction of large fuel flaming, the start of collapse, the fraction of collapse, the time when flame height above the fuel bed dropped below 30.48 cm (1.0 ft), the fraction of the fuel bed planform area in flaming or glowing, and the time when flaming and glowing ended. These observations were compared with the fractional weight-loss rate determined from the weight-loss record so that significant events in burning behavior could be evaluated in terms of weight-loss rate. The data related to the large-fuel burning rate are listed in table 2 and cover the period when the large-fuel burning dominates.

Figure 3—Burnout of experimental fuel bed. Flame lengths and the burnout of each size class of fuels were observed both visually and photographically.

Table 2—Burning rate, flame length, and other combustion characteristics determined during the burning of large fuel wood cribs

Identification of cribs	P Burn frac. sec-1	Ash hor. surf. area	Asv ver. surf. area	As-tot. tot. surf. area	Av vent area	P Porosity	Rr/As-tot. Unit area burn rate	Time of burn rate	Flame length	Frac. tot. bed remaining	Frac. large fuel remaining	Time to flame <1 ft	Tot. burn time	Residue left
Species-b-sr-n-N-/orient-mc	*sec-1*	*cm²*	*cm²*	*cm²*	*cm²*	—	*g/s-cm²*	*min*	*cm*	—	—	*min*	*min*	*gm*
DF- 5.08-1.00-12-4-H- 6.0	0.000816	72600	0	72600	3120	0.207	0.000790	11.00	274.0	0.486	0.581	29.0	128.0	-
PP- 5.08-1.00-12-4-H- 6.0	.000961	72600	0	72600	3120	.207	.000704	8.00	335.0	.414	.477	19.0	104.0	-
LP- 5.08-1.50-10-4-H- 6.0	.001110	64500	0	64500	4700	.269	.000740	8.40	335.0	.399	.475	20.0	89.0	-
SF- 5.08-2.23- 8-4-H- 6.0	.000703	54500	0	54500	6290	.339	.000475	9.00	243.0	.236	.293	15.0	112.0	-
DF- 5.08-2.23- 8-4-H- 6.0	.000682	54500	0	54500	6290	.339	.000578	9.00	304.0	.466	.578	17.0	94.0	-
LP- 5.08-2.23- 8-4-H- 6.0	.000840	54500	0	54500	6290	.339	.000547	9.60	182.0	.303	.376	23.0	73.0	-
PP- 5.08-2.23- 8-4-H- 6.0	.000622	54500	0	54500	6290	.339	.000425	8.33	243.0	.305	.378	14.1	95.0	-
PP- 5.08-3.00- 6-4-H- 6.0	.000473	35600	0	35600	5800	.403	.000330	9.00	97.5	.277	.359	11.5	89.0	322.0
SF-10.16-0.50- 8-4-H- 6.0	.000365	83800	0	83800	1260	.122	.000639	8.94	335.0	.814	.871	56.0	211.0	1010.0
LP-10.16-1.50- 5-4-H- 6.0	.000632	54900	0	54900	3710	.260	.000960	8.25	304.0	.582	.690	34.0	121.0	-
PP-10.16-1.50- 5-4-H- 6.0	.000516	54900	0	54900	3710	.260	.000835	9.63	274.0	.498	.572	24.0	132.0	712.0
SF-10.16-2.00- 4-4-H- 6.0	.000410	39600	0	39600	3710	.306	.000608	9.47	91.4	.591	.717	15.2	175.0	590.0
DF-10.16-2.50- 4-4-H- 6.0	.000384	47000	0	47000	5800	.351	.000706	7.42	182.0	.671	.794	18.0	286.0	2950.0
LP-10.16-2.50- 4-4-H- 6.0	.000371	47000	0	47000	5800	.351	.000561	8.70	121.0	.574	.710	15.5	151.0	681.0
PP-10.16-2.50- 4-4-H- 6.0	.000298	47000	0	47000	5800	.351	.000494	8.00	118.0	.821	1.000	10.0	238.0	-
PP-15.24-0.67- 5-4-H- 6.0	.000365	75500	0	75500	1660	.148	.000960	9.00	365.0	.786	.860	55.6	225.0	-
PP-15.24-1.00- 4-4-H- 6.0	.000371	55600	0	55600	2090	.193	.000987	9.00	304.0	.740	.819	30.0	242.0	1180.0
PP-15.24-2.50- 3-3-H- 8.0	.000204	36200	0	36200	5800	.400	.000512	8.90	30.4	.753	.884	8.9	376.0	-
PP-15.24-2.50- 3-4-H- 8.0	.000194	50600	0	50600	5800	.338	.000531	9.00	45.7	.719	.838	8.9	272.0	998.0
SF- 5.08-0.50-16-4-H-11.5	.000464	91300	0	91300	1450	.126	.000373	26.00	247.0	.392	.438	58.3	166.0	667.0
LP- 5.08-0.50-16-4-H-22.0	.000150	91300	0	91300	1450	.126	.000141	58.00	85.3	.250	.280	99.0	192.0	1530.0
DF- 5.08-3.00- 6-4-H-20.4	.000399	35600	0	35600	5800	.403	.000360	21.30	15.2	.410	.535	14.3	90.0	418.0
PP- 5.08-2.50- 7-4-H-20.0	.000525	43500	0	43500	5800	.365	.000379	18.20	30.4	.317	.399	22.2	117.0	-
DF-10.16-1.00- 6-4-H-13.7	.000394	63900	0	63900	2580	.200	.000831	11.00	304.0	.790	.888	40.7	223.0	989.0
DF-10.16-1.00- 6-4-H-22.0	.000243	63900	0	63900	2580	.200	.000516	21.30	213.0	.691	.776	36.0	218.0	8440.0
LP-10.16-2.50- 4-4-H-20.0	.000325	47000	0	47000	5990	.357	.000592	9.93	30.4	.635	.759	15.5	200.0	3000.0
SF-15.24-2.50- 3-4-H-20.0	.000162	50600	0	50600	5800	.338	.000469	8.78	27.4	.793	.925	5.0	690.0	2870.0
PP- 5.08-1.00-12-4-HV-6.0	.000959	76700	40800	117500	3120	.201	.000528	8.90	304.0	.358	.448	17.7	120.0	-
PP- 5.08-1.50-10-3-HV-6.0	.000855	47800	27800	75600	4700	.313	.000568	10.50	60.9	.178	.276	18.8	120.0	-
PP-10.16-1.00- 7-4-HV-6.0	.000483	81100	52000	133100	3710	.214	.000592	11.00	304.00	.507	.586	16.7	230.0	1430.0
PP-10.16-2.50- 4-3-HV-6.0	.000383	35500	26300	61800	6550	.429	.000586	8.27	152.00	.512	.861	10.5	119.0	1170.0
PP-15.24-0.75- 5-3-HV-6.0	.000325	58500	27800	86300	2090	.188	.000786	8.33	365.0	.739	.830	20.3	323.0	-
PP-15.24-1.50- 4-3-HV-6.0	.000370	48300	33400	81700	4700	.312	.000773	6.00	30.4	.726	.850	6.0	246.0	-
Date Used From Gross														
DF- 1.90-0.50- 7-10-H-9.2	.000900	5690	0	5690	32.4	.0755	.000333	-	-	-	-	-	-	-
DF- 1.90-1.25- 5-10-H-9.2	.002220	4510	0	4510	89.8	.1410	.000752	-	-	-	-	-	-	-
DF- 1.90-3.50- 3-10-H-9.2	.002170	2800	0	2800	176.0	.2500	.000700	-	-	-	-	-	-	-
DF- 1.90-0.50- 7- 7-H-9.2	.001130	3940	0	3940	32.4	.0907	.000427	-	-	-	-	-	-	-
DF- 1.90-1.25- 5- 7-H-9.2	.002230	3100	0	3100	89.8	.1700	.000761	-	-	-	-	-	-	-
DF- 1.90-3.50- 3- 7-H-9.2	.002100	1920	0	1920	176.0	.3030	.000697	-	-	-	-	-	-	-
DF- 1.90-0.50- 7- 5-H-9.2	.001480	2770	0	2770	32.4	.1080	.000560	-	-	-	-	-	-	-
DF- 1.90-1.25- 5- 5-H-9.2	.002250	2160	0	2160	89.8	.2030	.000781	-	-	-	-	-	-	-
DF- 1.90-0.50- 7- 3-H-9.2	.002050	1600	0	1600	32.4	.1420	.000833	-	-	-	-	-	-	-
DF- 1.90-1.25- 5- 3-H-9.2	.002150	1220	0	1220	89.8	.2700	.000795	-	-	-	-	-	-	-
DF- 2.54-0.50- 7-10-H-9.2	.000710	10100	0	10100	58.0	.0755	.000416	-	-	-	-	-	-	-
DF- 2.54-1.25- 5-10-H-9.2	.001340	8060	0	8060	160.0	.1410	.000689	-	-	-	-	-	-	-
DF- 2.54-3.50- 3-10-H-9.2	.001390	5010	0	5010	316.0	.2500	.000711	-	-	-	-	-	-	-
DF- 3.81-0.50- 7-10-H-9.2	.000760	18100	0	18100	362.0	.1410	.000565	-	-	-	-	-	-	-
DF- 3.81-1.25- 5-10-H-9.2	.000930	22900	0	22900	129.0	.0753	.000430	-	-	-	-	-	-	-
DF- 9.15-0.29- 8-10-H-9.2	.000180	141000	0	141000	336.0	.0485	.000401	-	-	-	-	-	-	-
DF- 9.15-0.50- 7-10-H-9.2	.000220	132000	0	132000	751.0	.0754	.000436	-	-	-	-	-	-	-

RESULTS

Because these fuel beds were made up of several fuel sizes, the contribution of the small fuels to the flaming and the weight loss was analyzed and the burnout of the 2.54-cm (1.0-in) fuels, 70 percent or more, gave the most consistent benchmark for the period where the burning and flaming was dominated by the large sized fuel. The fractional weight-loss rate was plotted against the time since ignition (fig. 4). The observed events were noted on the plot and assisted in the identification of the fractional weight loss rate associated with the large-fuel flaming burnout. The data presented by Gross (1962) for horizontally spaced fuels provided data points in the ventilation controlled region. These data points were merged with the data of the current study and used in equations 2, 3, and 4 to indicate how the unit exposed area burning rate changes with the porosity function. While Gross (1962) (fig. 5), Harmathy (1972a), Heskestad (1973), and Block (1971) have shown the unit surface area burning rate to increase with increasing porosity function in the ventilation-controlled region and to become steady in the surface-area-controlled region, this study shows the unit exposed area burning rate decreases when the porosity function becomes large (fig. 5). No clear separation of fuel size influence was found.

Distribution of the data points suggests that a parabolic or quadratic equation could describe the change in unit area burning rate with increasing porosity. The best fit was obtained with a quadratic equation which had the following expression:

$$R_r/A_s = -4.1273 \times 10^{-6} + 7.1923 \times 10^{-3}(P) - 1.6726 \times 10^{2}(P)^2 \quad (5)$$

$$R^2 = 0.7717$$

with the predicted value and the 95 percent confidence limits illustrated in figure 6. Fuel beds with horizontal and vertical spacing of large fuels had burn rates similar to that for horizontally spaced fuels. Burns at high moisture contents had more variability in burning rates, and they tend to decrease with increasing moisture. The peak unit area burning rate occurs at a porosity of about 0.22, which yields a value of 0.000789 g/cm^2–s. That is different from the steady rate of 0.00062 gm/cm^2–s previously reported. Evaluation of burning rate in other fuels, such as slash beds in the field, in terms of porosity are difficult because of the several dimensions that are needed. To simplify estimation of burning rates, I considered the physical properties Wilson (1982) introduced, $\sigma\beta\delta$, where σ is the fuel particle surface area-to-volume ratio, cm^2/cm^3; β is the packing ratio defined by the ratio of fuel bed bulk density to fuel particle density; and δ is the depth of the fuel bed, cm. These variables can be readily measured or reasonably estimated. To obtain comparable results, the inverse of $\sigma\beta\delta$ must be used so as to produce a ratio of planform area to fuel surface area. The difference is in the planform area. The porosity function uses the vent planform area while the $\sigma\beta\delta$ function uses the fuel bed planform area. The expected result is less correlation when the fuel bed planform area is used. This is true for the polynominal fit to data and can be seen in the curve fit (fig. 7).

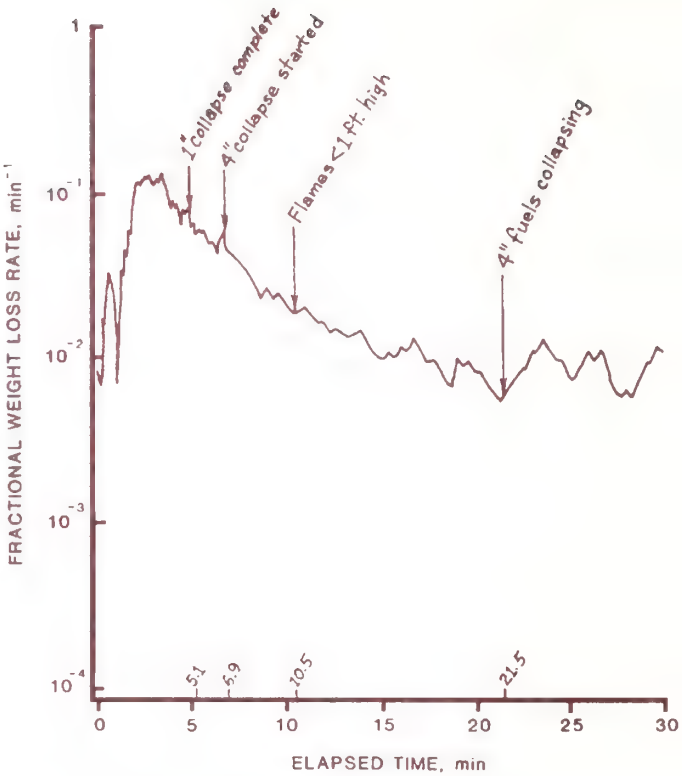


Figure 4—A plot of the fractional weight loss rate from the time of ignition to burnout. Significant events during the fire were noted by observers.

$$R_r/AS_{tot} = -4.56505 \times 10^{-5} + 2.717368 \times 10^{-3}(1/\sigma\beta\delta)^{.5} + 1.569299 \times 10^{-3}(1/\sigma\beta\delta) - 2.23657 \times 10^{-2}(1/\sigma\beta\delta)^2 \quad (6)$$

$$R^2 = 0.6957$$

The same type of response was found in the independent observations of flame length made during each fire. The flame height associated with burning rate per unit area of exposed large-fuel surface area was found to display a sharp decrease at porosities above 0.3 (fig. 8a). Flame length values for the three large-fuel sizes, 5, 10, and 15 cm, range along a steep line between porosity values of 0.30 and 0.40. Generally, the fuel beds near this porosity did not support flaming combustion long, but did have a long smothering pyrolysis period prior to going into the glowing combustion phase of the burnout.

Similar data distribution is exhibited when flame length is plotted against the fuel bed descriptor, $1/\sigma\beta\delta$ (fig. 8b). The shifts along the axis result in part from the variation in β because of species differences in specific gravity. Species may also have other influences on volatile production and combustion, but data are insufficient to support any conclusions. Gross's (1962) data did not include measurements of flame length, thus expected flame lengths can be inferred only by use of the break point between the ventilation-controlled section and the exposed surface area section shown in figure 5. The dotted lines in figures 8a and 8b are positioned by this inference, assuming flame length nears zero when the porosity function or the fuel bed descriptor approaches zero.

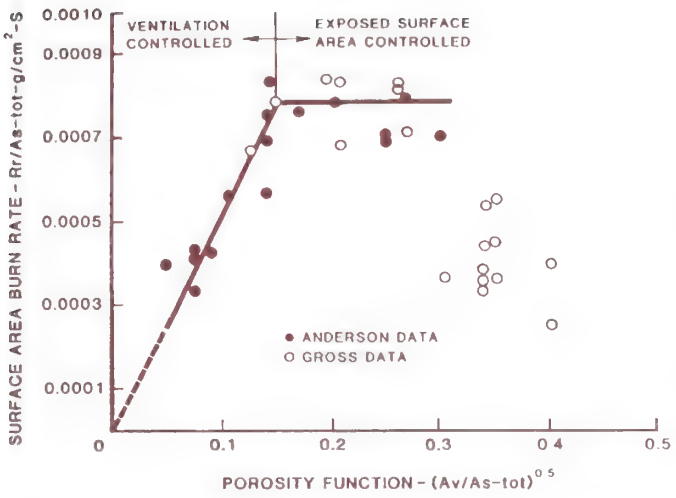


Figure 5—Relationship of surface area burning rate to porosity function. The surface area burning rate increases in the ventilation = controlled region to a maximum near 0.00078 g/cm²–s which holds nearly constant until the porosity function increases to 0.30 or greater where the burning rate decreases. Closed circles are data from Gross (1962) and open circles are data from the current study.

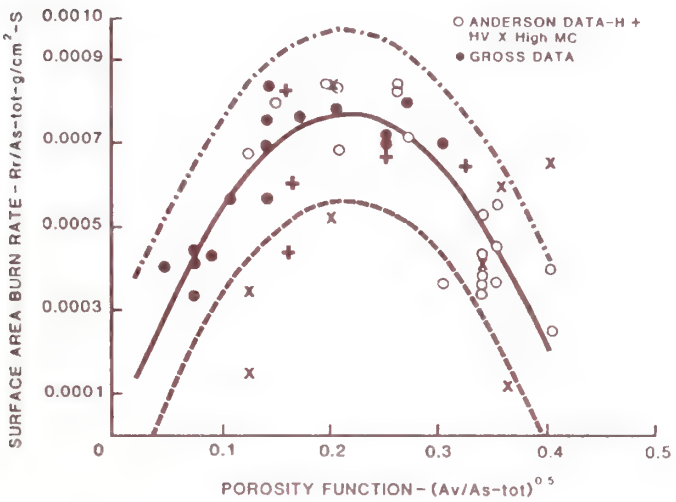


Figure 6—The response of the surface area burning rate to changing porosity. This phenomenon can be modeled by a quadratic equation—equation 4—shown by the solid line. The 95 percent confidence limits are shown by the dotted lines. The closed circles are data from Gross (1962), the open circles are data from the current study for fuels at mc less than 10 percent with horizontal spacing only, the plus symbols are for fuels with mc less than 10 percent and vertical and horizontal spacing, and the crosses are for fuels with horizontal spacing and mc greater than 10 percent.

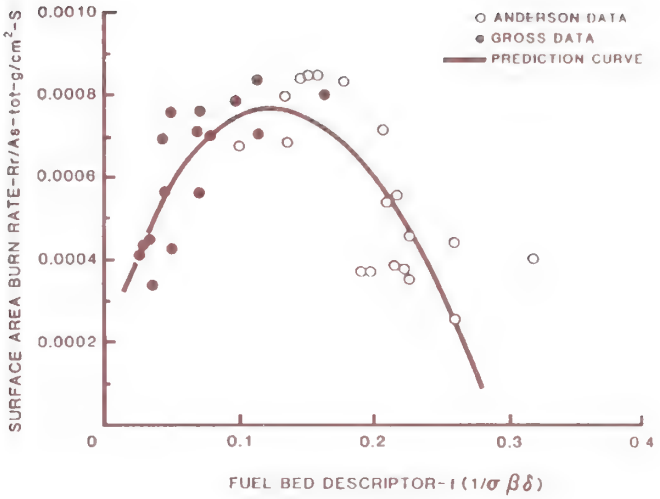
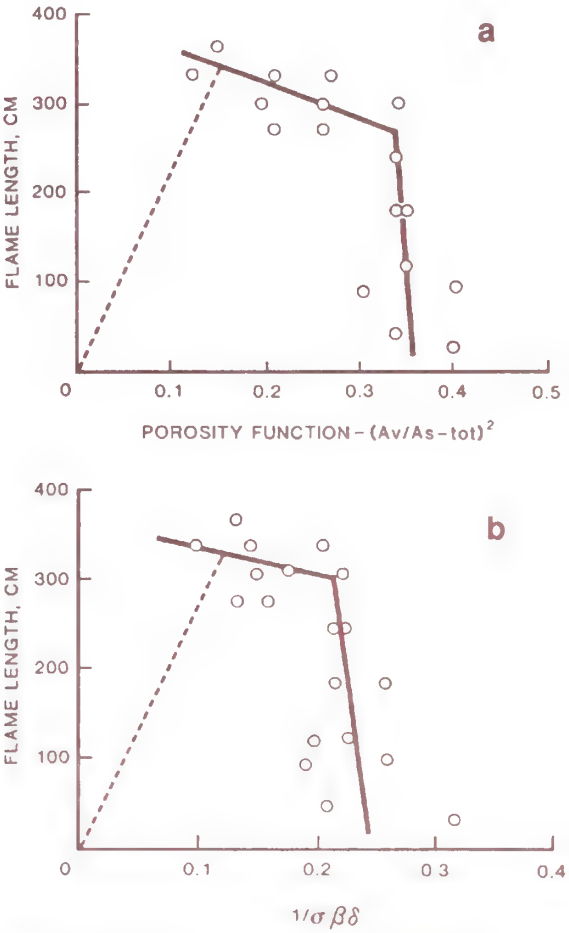


Figure 7—Relationship of surface area burning rate to fuel bed description. The surface area burning rate can be predicted by a quadratic equation—equation 5—in terms of a fuel bed descriptor, $1/\sigma\beta\delta$, and is more suited to field application. Symbols are the same as in figure 5.



Figures 8a and 8b—Relationship of flame length to porosity and fuel bed descriptor. Flame length shows the same decrease as the burning rate as porosity or the fuel bed descriptor increases. A sharp decrease in flame length occurs at a porosity of 0.34 or a fuel bed descriptor value of 0.22. Data are from current study only.

A limited number of burns were conducted with large fuels at higher moisture contents to examine the resultant change in burning properties. Moisture contents of 11 to 14 percent and 20 to 22 percent were established for some burns, as documented in tables 1 and 2. Except for two fires at 11 to 14 percent mc, the fires were close to the curve that describes the quadratic equation for R_r/A_s as a function of the porosity (fig. 6). An estimate of the burning rate is possible with equation 4, but it is unknown whether it would apply to higher mc's. In the Pacific Northwest some prescribed burning is being done when mc's in large uncured fuels range from 63 to 113 percent (Ottmar 1987).

Some burns were conducted where the large fuels were spaced vertically and horizontally to evaluate the effect on burning rate. The results indicate that slightly higher unit area burning rates occur with spacing in both dimensions (table 2).

DISCUSSION AND SUMMARY

The critical spacing value of 2.23:1 assigned by Albini (1976b) appears to be close to the maximum spacing for large fuels for sustaining the flaming combustion phase of fuel burnout and corresponds to a porosity factor near 0.34 or a fuel bed descriptor value of 0.22. The current work indicates the 5-, 10-, and 15-cm (2-, 4-, and 6-in)-thick fuels cluster as the unit area burning rate decreases with increasing porosity or fuel bed descriptor. A porosity value of 0.34 seems to be very close to the limit of flaming combustion for large fuels, those greater than 2.54 cm (1.0 in) in thickness. Although flaming combustion may not be supported, the large fuels continue to pyrolyze and char, causing the release of numerous gaseous products until the large fuels have been consumed.

At 6 percent mc, all of the fuel beds were very nearly consumed but total consumption took up to 4 hours or more. At higher moisture contents the large fuels do not completely burn up and residues remain (table 2). Ottmar (1987) pointed out that large-fuel reduction is a function of the internal moisture content where the reduction was measured as the diameter reduction. The current work shows only the initial results for dry fuels; as fuels increase in moisture, the amount unburned will increase (table 2). Experience suggests that although moisture content influences the burnout, once pyrolysis is established large fuels burn rather completely up to 20 percent mc.

The experimental results of this study indicate that area burning rate eventually peaks and that this occurs in the vicinity of a porosity of 0.22 (fig. 6). The maximum value of 0.00078 g/cm^2–s is near the value of 0.00062 g/cm^2–s reported for the surface area controlled region of porosity. Earlier work in the modeling of wildland free-burning fires (Rothermel 1972) indicated that there can be optimum burning conditions where the fire reaction intensity may peak. Wilson (1982), in his reexamination of data from spreading fire, did not find well-defined peaks but rather broad indefinite peaks as reaction intensity was evaluated in terms of packing ratio. He stated that stationary fires might portray the optimum packing ratio more accurately than data from moving fire fronts. The results of the current work were merged with Wilson's (1982) data for 0.635- and 1.37-cm (1/4- and 1/2-inch)-thick ponderosa pine sticks to investigate relationship of the fuel bed descriptor $1/\sigma\beta\delta$ and flame length in both stationary and moving fires. Similarly to stationary fires, moving fire fronts do exhibit a drop in flame length as $1/\sigma\beta\delta$ increases beyond 0.22 but maintain low flame height in thin fuels out to approximately 0.80 for $1/\sigma\beta\delta$ (fig. 9). Although similar responses are apparent, loading and moisture content must be studied before the behavior of moving and stationary fires can be fully compared. In addition, burning of fine fuels in a fuel bed of mixed sizes will result in higher flame heights than observed when only fine fuels make up the fuel bed. Because the burnout of the large

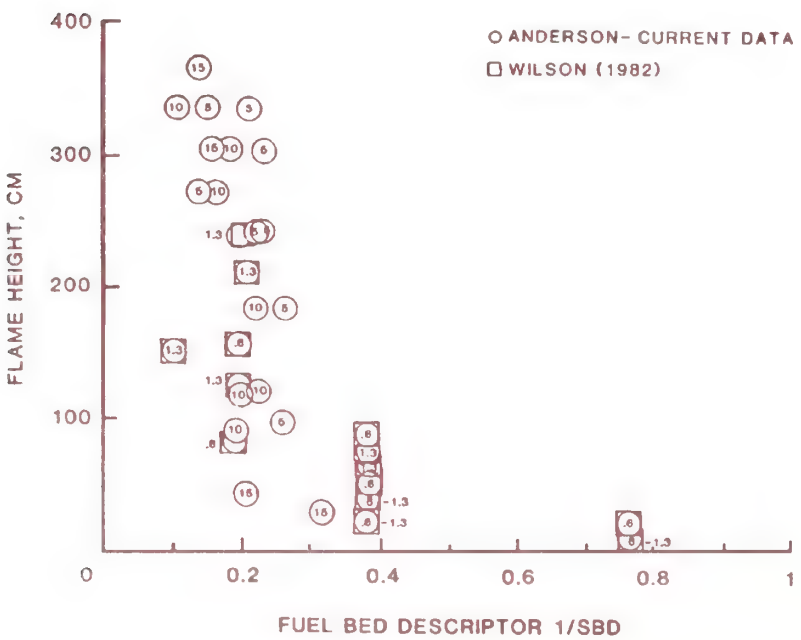


Figure 9—Merging of data from Wilson (1982) with current study data. Plotting shows a sharp decrease in flame length at fuel bed descriptor values at 0.22 and above for both moving and stationary fires. Numbers within the data symbols denote the fuel particle thickness in centimeters.

fuels takes place after the fire front has passed, linking behavior of moving fires and stationary fires could be valuable in assessing the thermal impacts of a wildland fire.

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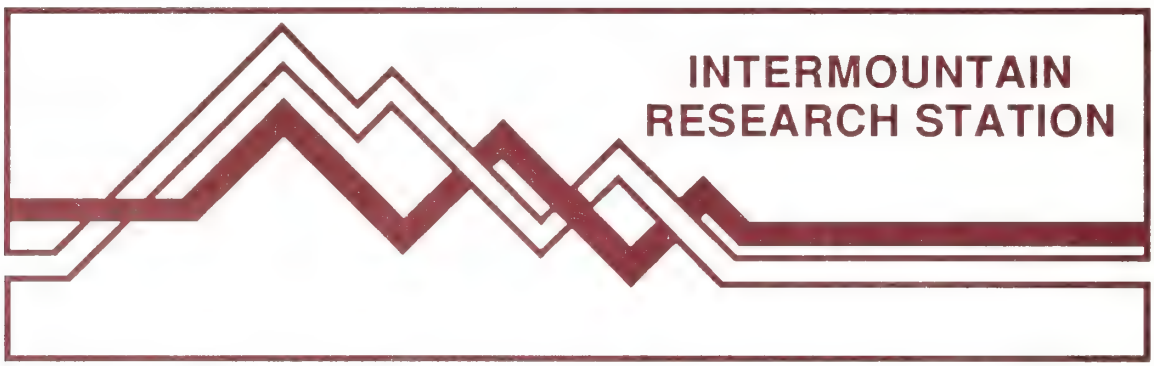
Flaming combustion in cribs of large woody fuels, thickness 5 cm or greater, is not sustained when fuel spacing ratio, fuel edge-to-edge separation distance to fuel thickness, is greater than 3:1. The flame length associated with the large-fuel burning rate was found to drop rapidly when the large-fuel spacing ratio increases beyond 2.23:1. This supports the critical spacing assigned in the large-fuel subroutine burnout of Albini's fire modeling program.

KEYWORDS: fuels, fire behavior, spacing, burning rates



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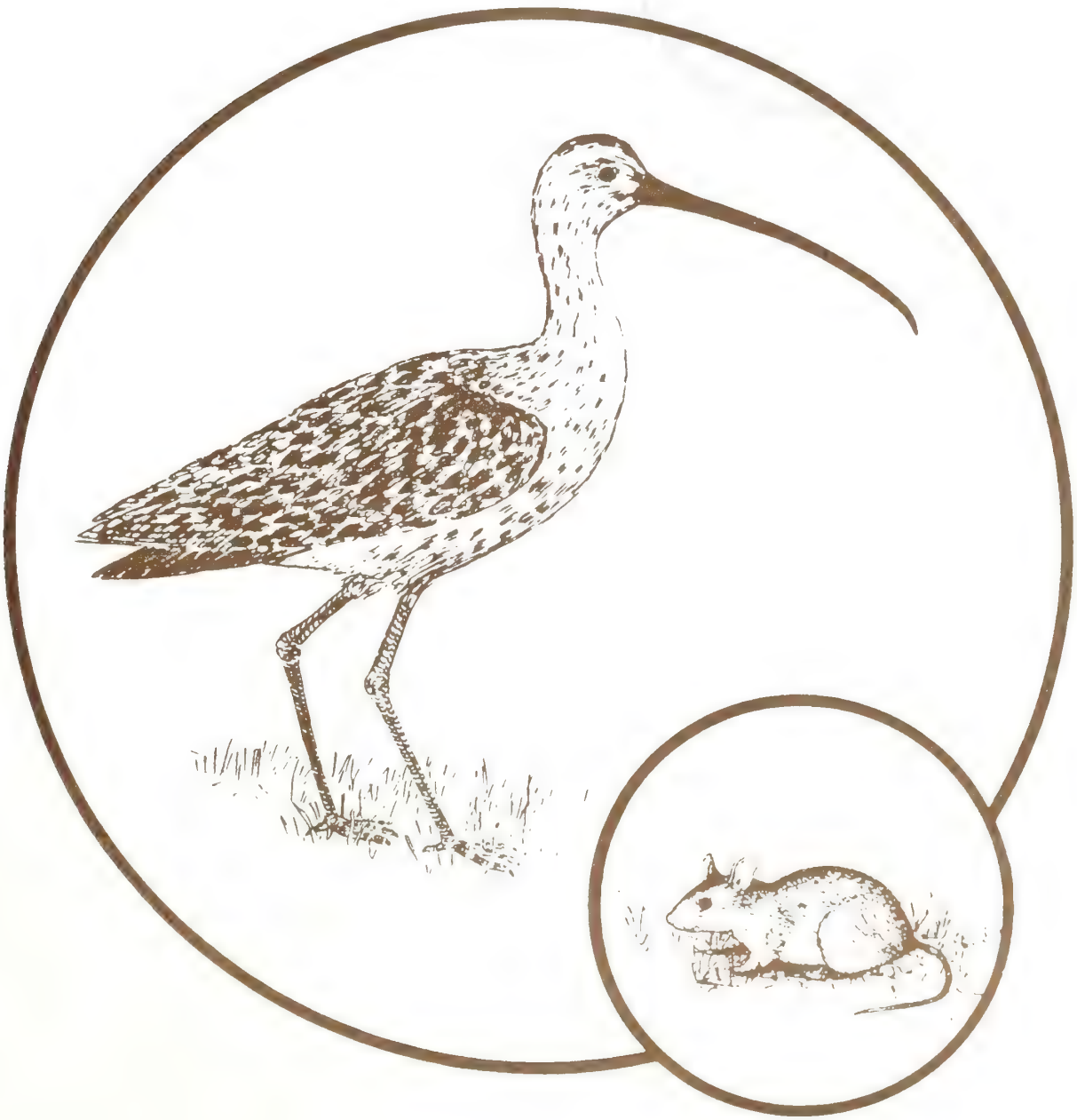
Bird and Small Mammal Populations in a Grazed and Ungrazed Riparian Habitat in Idaho

Dean E. Medin
Warren P. Clary



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RESEARCH SUMMARY

We compared breeding bird and small mammal populations between a riparian habitat seasonally grazed by cattle and a comparable adjacent riparian habitat protected from grazing for the previous 14 years by a fenced exclosure. The 122-ha exclosure, constructed in 1975, straddles Summit Creek in east-central Idaho. Bird populations were assessed by spot-mapping methods in the spring of 1989. Small mammal populations were compared by removal trapping in late summer of both 1988 and 1989.

There was little difference between grazed and ungrazed habitats in total breeding bird density. But total bird biomass, bird species richness, and bird species diversity were 1.87, 1.75, and 1.62 times higher, respectively, in the grazed habitat. The differences were almost entirely due to the presence of shorebirds—killdeer, willets, and long-billed curlews—as breeders only on the grazed area. Those species are frequently associated with the low vegetational profiles of grazed habitats. Other species, including savannah sparrows and red-winged blackbirds, were more numerous in the ungrazed habitat.

Small mammal populations were almost a third higher on the grazed area than on the ungrazed area. Conversely, both species richness and species diversity of small mammal communities were higher in the ungrazed habitat. Deer mice were the most frequently trapped small mammal on both the grazed and ungrazed areas. They were almost twice as common in the grazed habitat. Montane voles were found in highest densities in the ungrazed habitat. Those two species accounted for 94 percent of the total number of individual animals trapped at Summit Creek. Other species, including vagrant shrews, water shrews, and Great Basin pocket mice, were caught irregularly and in smaller numbers.

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Bird and Small Mammal Populations in a Grazed and Ungrazed Riparian Habitat in Idaho

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Warren P. Clary

INTRODUCTION

Livestock grazing in riparian ecosystems has been a recent focus of rangeland management in the Western United States (Swanson 1988). Cattle prefer riparian areas for the quality and variety of forage, for easy accessibility, for shade, and for a generally reliable source of water (Ames 1977; Gillen and others 1985; Martin 1979). Riparian ecosystems are similarly important to wildlife. Many species of wildlife are either directly dependent on riparian habitats or utilize them more than other habitats (Thomas and others 1979).

Several studies have reported adverse effects of cattle grazing on riparian vegetation, and recovery of vegetation when grazing is modified, reduced, or eliminated (Ames 1977; Knopf and Cannon 1982; Rickard and Cushing 1982; Taylor 1986; Winegar 1977). Recovery of riparian vegetation following removal of livestock can be dramatic. If habitat deterioration is not severe, herbaceous vegetation can increase significantly within several growing seasons (Platts and Nelson 1984), and woody vegetation may recover within 5 to 10 years (Rickard and Cushing 1982; Skovlin 1984). But severely deteriorated habitats may require long recovery times, perhaps decades (Knopf and Cannon 1982) or more (Platts and Raleigh 1984).

Exclosures, natural areas, and other areas that have received minimal use by livestock are often used as reference areas on rangelands (Kauffman and Krueger 1984; Ohmart and Anderson 1986). Livestock exclosures provide opportunities to study vegetation and associated wildlife communities on ungrazed as compared to grazed habitats. This report compares breeding bird and small mammal populations between a riparian habitat seasonally grazed by cattle and a comparable adjacent riparian area protected from grazing for the previous 14 years by a fenced exclosure. The 122-ha exclosure, constructed in late 1975, is on Summit Creek in east-central Idaho. Bird populations were assessed in the spring of 1989. Small mammal populations were compared by removal trapping during late summer of both 1988 and 1989.

Common and scientific names of birds and small mammals referred to in this paper are listed in the appendix.

STUDY AREA

The Summit Creek study area is 41 km north of Mackay in Custer County, ID, at an elevation of about 1,975 m. It is near the southern boundary of the Northern Rocky Mountains physiographic province (Fenneman 1931) in the Little Lost River drainage. Summit Creek originates from springs and flows through a gently sloping, basinlike valley bounded on the east by the Lemhi Range and on the west by the Lost River Range. The mountain ranges are rugged and serrated and chiefly composed of limestone, dolomite, quartzite, shale, and schist (Kirkham 1927).

Regional climate is semiarid. Average annual precipitation at Mackay (elevation 1,797 m) is 247 mm, with peaks in May and June. The growing season is short, averaging less than 100 days at Mackay (USDC NOAA 1982). Microrelief in many parts of the riparian area is hummocky, with soils high in total salts (USDA SCS 1987). The riparian zone seldom exceeds 50 to 100 m in width.

Several vegetation community types were identified in the riparian area and adjoining upland. For our study, we consolidated the community types into three general categories: sagebrush (*Artemisia* spp.)/upland, mat muhly (*Muhlenbergia richardsonis*)/hummock, and mesic herbaceous. The sagebrush/upland type occupies the gentle slopes and terraces adjoining the riparian zone. The other two types—mat muhly/hummock and mesic herbaceous—were considered components of the riparian habitat.

Upland vegetation on the site is shrub-steppe (West 1983). The dominant shrubs are low sagebrush (*A. arbuscula*) and threetip sagebrush (*A. tripartita*), with occasional individuals of green rabbitbrush (*Chrysothamnus viscidiflorus*), gray horsebrush (*Tetradymia canescens*), and big sagebrush (*A. tridentata*). The herbaceous stratum commonly includes Sandberg's bluegrass (*Poa sandbergii*), bluebunch wheatgrass (*Agropyron spicatum*), aster (*Aster* spp.), and long-leaf phlox (*Phlox longifolia*). The hummocky areas are dominated by herbaceous species, most notably mat muhly and thick-spiked wheat-grass (*A. dasystachyum*), and including Kentucky bluegrass (*P. pratensis*), tufted hairgrass (*Deschampsia cespitosa*),

short-beaked sedge (*Carex simulata*), and Kelsey's phlox (*P. kelseyi*). The stream is closely bordered by clumped communities of Kentucky bluegrass, beaked sedge (*C. rostrata*), and Baltic rush (*Juncus balticus*). Associated forbs and graminoids include mannagrass (*Glyceria* spp.), water sedge (*C. aquatilis*), Nebraska sedge (*C. nebraskensis*), American bistort (*Polygonum bistortoides*), and large-leaved avens (*Geum macrophylum*).

The study area is located largely on public lands administered by the Bureau of Land Management, U.S. Department of the Interior. Recent (1976 to 1989) stocking levels have varied from about 1,000 to 2,000 animal unit months (AUM's), with a grazing season from about mid-May to late October (Hale 1989). Stocking levels and grazing periods are adjusted annually on the basis of current resource conditions.

METHODS

Two 9-ha plots, one in the upper (westernmost) section of the exclosure and the other in the adjacent (upstream) grazed riparian area, were censused for breeding birds using the spot-map method (International Bird Census Committee 1970). Plot locations were selected on the basis of similarities in topography and vegetation between the grazed and ungrazed environments. The census plots, 600 by 150 m, were oriented lengthwise along Summit Creek and gridded with transects crossing the stream channel. Both plots straddled the riparian zone and included part of the extensive uplands. Grid points were surveyed and marked with numbered stakes at 25-m intervals.

Eleven census visits were made to each plot from May 17 to June 29, 1989. The same observer (DEM) conducted the censuses on both plots. Most of the spot-mapping was done from sunrise to early afternoon when birds were most active. Census routes were varied by choosing different routes through the plot, with different starting and ending points. To ensure complete coverage, the plot was censused by walking within 25 m of all points on the grid. Observations and registrations extended well beyond plot boundaries.

At the end of the sampling period, clusters of observations and coded activity patterns on species maps were circled as indicating areas of activity or approximate territories (International Bird Census Committee 1970). Fractional parts of boundary territories were included. Oelke (1981) summarized methodological difficulties and other special problems of the mapping method. We followed Hill (1973) for estimates of species diversity.

A 1.7-ha trapping grid was located in each of the grazed and ungrazed study plots to estimate small mammal populations. Trapping grids were placed near the center of the 9-ha plots established to census bird populations. Each grid measured 225 by 75 m and consisted of 40 trapping stations systematically spaced at 25-m intervals in 10 rows and 4 columns. The rectangular grids were positioned lengthwise along Summit Creek and straddled the stream channel. Two Museum Special mouse traps and one Victor rat trap were placed near each trapping station. Traps were baited with a mixture of peanut butter and rolled oats and examined daily for 5 consecutive days from August 3 to August 7, 1988, and from August 17 to August 21, 1989.

Vegetation and other features of the grazed and ungrazed study plots were measured from July 17 to August 30, 1989. Twenty sample locations were established within each of the three plant community types for a total sample size of 60 per study plot. A 50- by 50-cm (0.25-m^2) quadrat was located at each of the systematically positioned sample locations. Canopy cover (Daubenmire 1959) was ocularly estimated for the total of each plant life form (graminoid, forb, shrub) and recorded as the midpoint of one of eight percent-cover classes (0-1, 1-5, 5-10, 10-25, 25-50, 50-75, 75-95, 95-100). Percentages of litter, rock, bare ground, and lichen-moss were similarly estimated. The vegetative height (excluding flower and seed-head heights) of each graminoid, forb, and shrub nearest the center of each quadrat was measured.

Biomass of graminoids, forbs, and shrubs was determined by clipping vegetation from ground level upward within a vertical projection from the 0.25-m^2 quadrats. Clipped materials were bagged, ovendried, and weighed.

Plant names follow Hitchcock and Cronquist (1973). Bird nomenclature is from the 1983 AOU Check-list (American Ornithologists' Union 1983). Scientific and common names of mammals follow Jones and others (1986).

RESULTS AND DISCUSSION

We found structural (physiognomic) differences in the vegetation between grazed and ungrazed habitats on Summit Creek. Those differences were apparently reflected in the organization of associated breeding bird and small mammal communities.

Vegetation

The most evident structural difference in the vegetation was in the height values where graminoid, forb, and shrub height means were significantly reduced on the grazed site (table 1). Other differences were primarily in the herbaceous layer where graminoid and forb biomass and graminoid canopy cover values were lower on the grazed site. Graminoid biomass on the grazed plot was only about one-seventh that inside the exclosure. Estimates of forb and shrub cover were similar on the grazed and ungrazed areas. There was significantly more rock coverage on the grazed plot. Shrub biomass and shrub, bare ground, and litter coverage were similar. Lichen-moss cover values were slightly higher on the grazed site. There were no tall shrubs or trees on the study plots.

Birds

We recorded eight species of birds breeding on the Summit Creek study site; seven species bred on the grazed plot and four species bred on the ungrazed plot (table 2). Vesper sparrows, savannah sparrows, and western meadowlarks were found as breeding birds on both the grazed and ungrazed plots. Killdeer, willets, long-billed curlews,

Table 1—Vegetation and other features of grazed and ungrazed study plots, Summit Creek, ID, 1989

Item	Ungrazed Mean[1]	Ungrazed SD	Grazed Mean[1]	Grazed SD	P[2]
Graminoid					
Biomass (g/m²)	267.6	254.2	36.7	30.8	<0.01
Canopy cover (%)	61.6	30.5	51.9	30.3	.08
Height (m)	.18	.09	.06	.03	<.01
Forb					
Biomass (g/m²)	24.9	29.8	11.9	14.6	<.01
Canopy cover (%)	12.0	13.2	11.5	11.9	.81
Height (m)	.07	.05	.03	.02	<.01
Shrub					
Biomass (g/m²)	71.1	164.5	75.0	212.7	.91
Canopy cover (%)	7.4	14.5	7.3	13.9	.97
Height (m)	.34	.21	.26	.12	.01
Other					
Bare ground (%)	20.3	25.0	23.3	24.2	.50
Litter (%)	10.4	11.5	9.1	11.6	55
Rock (%)	.64	1.52	2.27	5.89	.04
Lichen-moss (%)	.30	1.15	.84	2.27	.10

[1] $n = 60$ except for forb and shrub height means for which n ranged from 50 to 58.
[2] Probability associated with unpaired t-tests. P of less than 0.10 was considered significant.

and Brewer's blackbirds were territorial only on the grazed area. Red-winged blackbirds nested only on the ungrazed plot. Wide-ranging raptorial birds, although commonly seen, were not included in the analysis. Transient species were also excluded. Other birds, observed as visitors to the study site, are listed in the appendix.

We found little difference between the grazed and ungrazed plots in total breeding bird density (table 2). But estimates of total bird biomass differed markedly on the two plots. Biomass on the grazed plot (226 g/ha) was almost twice that (121 g/ha) on the ungrazed plot (table 2). The difference in total biomass was almost entirely due to the presence of large shorebirds (killdeer, willet, long-billed curlew) that were breeders only on the grazed plot. Species richness and our estimate of bird species diversity (the reciprocal of Simpson's index) were larger on the grazed plot, again as a result of the presence of the three shorebirds that established breeding territories only on the grazed plot.

Curlew populations are declining in some areas of the Western United States as habitat is lost to agriculture and other land development (Ryser 1985). It is a short-to-midgrass prairie nesting species (Pampush 1980), often nesting in moist meadows near streams and lakes, as well as dry upland habitats (Harrison 1979). Long-billed curlews prefer breeding habitats containing short grass, bare ground, shade, and abundant invertebrate prey (Pampush 1980). Livestock grazing tends to maintain the low vegetational profile apparently preferred by curlews as breeding habitat. At Summit Creek, we observed them most often near the stream in mesic herbaceous communities dominated by grasses, sedges, and rushes.

Killdeer and willets also nest in open habitats where vegetation is sparse and low, usually within short flight distances to feeding areas (Palmer 1967). Both are ground-inhabiting species, building their nests and foraging there. We saw willets most often wading in the stream or pecking and probing for insects along the shoreline. Killdeer were usually seen either in flight or on the ground within a few meters of the stream in the most open habitats. Distraction displays and other territorial behaviors exhibited by both the killdeer and willet were noted only on the grazed plot. Taylor (1986) reported a positive response by killdeer to grazing in southeastern Oregon. In North Dakota, killdeer and willets were observed in significantly greater densities in grazed habitats (Renken and Dinsmore 1987).

Savannah sparrows, numerically dominant on both study plots, were found in greater numbers on the ungrazed plot (table 2). Kantrud (1981) similarly found a negative response by savannah sparrows to grazing in North Dakota native grasslands. A preference of this species for idle or lightly grazed areas was also noted by Owens and Myres (1973). This sparrow frequents open fields and meadows and is most commonly found in moist, grassy habitats in Idaho (Burleigh 1972). It is usually restricted to the vicinity of streams, ponds, lakes, and irrigation systems—often where soils are alkaline (Ryser 1985). Savannah sparrows have an affinity for habitats with a rank growth of vegetation and a dense ground cover (Linsdale 1938), a condition existing in more abundance in the ungrazed habitat on the Summit Creek site. Most savannah sparrow territories on the study area were located in the mat muhly/hummock community type although other plant communities were often included within territorial boundaries.

Table 2—Density (pairs/40 ha), diversity, and other attributes of breeding bird populations on grazed and ungrazed study plots, Summit Creek, ID, 1989

Species	Foraging guild[1]	Nesting guild[2]	Density Ungrazed	Density Grazed
Killdeer	GGI	GRN	[3]+	4.4
Willet	SPI	GRN	+	3.1
Long-billed curlew	GFO	GRN	+	1.8
Vesper sparrow	GFO	GRN	8.4	7.6
Savannah sparrow	GFO	GRN	39.1	24.9
Red-winged blackbird	GFO	CRN	12.0	+
Western meadowlark	GGI	GRN	8.0	6.2
Brewer's blackbird	GFO	GBN	+	17.3
Total pairs/40 ha			67.5	65.3
Total individuals/km²			338	327
Biomass[4] (g/ha)			121	226
Species richness (n)			4	7
Species diversity[5] ($1/\Sigma p_i^2$)			2.52	4.07

[1] After DeGraaf and others (1985). GGI = ground gleaning insectivore, SPI = shoreline probing insectivore, GFO = ground foraging omnivore.
[2] After Harrison (1979). GRN = ground nester, CRN = cattail, rush, sedge, reed, grass, and bush nester, GBN = ground and bush nester.
[3] + indicates bird observed infrequently (less than three registrations).
[4] Species weights from Dunning (1984).
[5] After Hill (1973). Here, p_i is the proportional abundance of the n species in a sample.

Vesper sparrows and western meadowlarks were both found in similar densities on grazed and ungrazed plots (table 2). Both species mainly frequent grasslands and open, low-growing shrub habitats (Ryser 1985). Both forage and nest on the ground. At Summit Creek, we found vesper sparrows most often in the sagebrush/upland community type. Western meadowlarks were distributed thoughout the grazed and ungrazed plots. Vesper sparrows and western meadowlarks were negatively affected by livestock grazing in northern Nevada (Page and others 1978). In North Dakota, western meadowlarks were about equally common under three levels of grazing intensity (Kantrud 1981), and in Oklahoma, Smith (1940) found that only severe overgrazing made conditions unsuitable for the western meadowlark.

Red-winged blackbirds were found as breeding birds only on the ungrazed plot (table 2). Conversely, Brewer's blackbirds were territorial only on the grazed plot. Nests of the red-winged blackbird were bound to tall, coarse stalks of beaked sedge found in thick stands near the stream. Heights of beaked sedge communities in the grazed plot were considerably reduced as a result of livestock grazing, thereby essentially eliminating potential nesting habitat for red-winged blackbirds. Nests of Brewer's blackbirds were on the ground in tussocks of grasses and forbs or beside a clod of dry manure. Taylor (1986) found red-winged blackbirds more abundant in undisturbed or rarely grazed riparian habitats in southeastern Oregon. In North Dakota, Kantrud (1981) found that red-winged blackbird populations were greatly reduced or extirpated by heavy grazing.

Small Mammals

Six species of small mammals were trapped during two seasons of study at Summit Creek (table 3). Deer mice and montane voles accounted for over 94 percent of 115 individual animals trapped. Each of those species was trapped on both grazed and ungrazed study plots. Other species were caught irregularly and in smaller numbers.

Table 3—Relative abundance, naive density, and other attributes of small mammal populations on grazed and ungrazed study plots, Summit Creek, ID, 1988 and 1989

Species	Foraging guild[1]	Relative abundance (*n*/100 trap nights)		Naive density[2] (*n*/ha)	
		Ungrazed	Grazed	Ungrazed	Grazed
Vagrant shrew	INS				
1988		0.2	0.0	0.6	0.0
1989		.0	.0	.0	.0
Water shrew	INS				
1988		.2	.0	.6	.0
1989		3	0	1.2	.0
Northern pocket gopher	HER				
1988		.2	.0	.6	.0
1989		0	.0	.0	.0
Great Basin pocket mouse	GRA				
1988		.2	.0	.6	.0
1989		.0	.0	.0	.0
Deer mouse	OMN				
1988		2.7	5.2	9.5	18.3
1989		1.3	4.8	4.7	17.2
Montane vole	HER				
1988		1.5	.8	5.3	3.0
1989		1.8	.0	6.5	.0
Total naive density (*n*/ha)					
1988				17.2	21.3
1989				12.4	17.2
Biomass (g/ha)					
1988				304	354
1989				283	282
Species richness (*n*)					
1988				6	2
1989				3	1
Species diversity[3] ($1/\Sigma p_i^2$)					
1988				2.47	1.31
1989				2.33	1.00

[1]After Martin and others (1951). INS = insectivore, HER = herbivore, GRA = granivore, OMN = omnivore.
[2]After Wilson and Anderson (1985). Effective trapping area and grid size are assumed to be equal.
[3]After Hill (1973). Here, p_i is the proportional abundance of the *n* species in a sample.

Four species—vagrant shrews, water shrews, northern pocket gophers, and Great Basin pocket mice—were trapped only in the ungrazed habitat. In 1989, only the deer mouse was caught on the grazed site.

Estimated small mammal density was almost a third higher in the grazed habitat (table 3). Total biomass values, however, were similar between the grazed and ungrazed plots. Also, small mammal species richness and our estimates of small mammal species diversity were larger within the exclosure. Each of the six species recorded during the study was trapped in the ungrazed habitat. Only two species were trapped in the grazed habitat.

Deer mice were the most frequently trapped small mammal in both the grazed and ungrazed habitats (table 3). Naive density (Wilson and Anderson 1985) on the grazed plot was more than twice that on the ungrazed plot. Most of the deer mice were trapped in the sagebrush/upland community type that occupied the slopes and terraces adjoining the riparian zone. They were trapped infrequently in mesic herbaceous and mat muhly/hummock communities that made up the riparian habitat. Brown (1967a) also trapped deer mice more commonly in areas distant from water as compared to those adjacent to water.

The deer mouse is one of the most widespread and generalized of all North American rodents (Baker 1968). It is Idaho's most common mammal (Larrison and Johnson 1981). They are found in diverse habitats including swamps, waterways, forests, grasslands, and deserts, and among rocks and cliffs (Larrison and Johnson 1981). It occupies a variety of plant successional stages (Thomas 1979). Higher densities on the grazed plot at Summit Creek suggest a tolerance by the deer mouse of habitats with a low, sparse herbaceous layer. Samson and others (1988) found deer mice frequently associated with low values of grass and litter cover as well as the presence of shrubs.

Others have reported contradictory results when comparing the abundance of deer mice in grazed versus ungrazed habitats. Kauffman and others (1982) found more deer mice in eastern Oregon riparian habitats after late-season grazing (late August to mid-September) than in ungrazed riparian habitats. But by late summer of the following year, and before grazing, the species composition of small mammal communities was not significantly different between grazed and ungrazed plots. Similarly, Moulton (1978) reported a positive response by deer mice to grazing in a cottonwood (*Populus sargentii*) riparian habitat in eastern Colorado. Samson and others (1988) also found deer mouse densities consistently higher on grazed pastures. Conversely, Rucks (1978) reported fewer deer mice in grazed versus ungrazed riparian communities. Hanley and Page (1982) found a positive response by deer mice to grazing in mesic habitats and a negative response in dry habitats.

Unlike the deer mouse, highest densities of the montane vole occurred in the ungrazed area (table 3). Four times as many montane voles were trapped on the ungrazed plot than on the grazed plot. Most were trapped in streamside habitats with the frequency of capture highest in mesic herbaceous communities. None were trapped in the sagebrush/upland community type. Montane voles occur most commonly in moist, weedy, or brushy areas near water at the edge of grasslands (Larrison and Johnson 1981). The importance of vegetative cover to the montane vole has been well documented (Brown 1967a; O'Farrell and Clark 1986). Grass seems to be a desirable component of the habitat (Randall and Johnson 1979). In eastern Oregon, high pregrazing populations of montane voles were either drastically reduced or eliminated after late-season grazing (Kauffman and others 1982).

Vagrant shrews and water shrews, both scarce on the study plots, were trapped only on the ungrazed area (table 3). Captures were irregular and consisted of only one or two animals in each trapping period. All were caught near the stream in mesic herbaceous communities. Vagrant shrews prefer moist, grassy habitats (Spencer and Pettus 1966), but they occur in a variety of other habitats including forests and shrublands (Brown 1967b). Water shrews are typically found along edges of swift-flowing streams with rocks, logs, crevices, and overhanging banks (Beneski and Stinson 1987). Kauffman and others (1982) reported reduced populations of the vagrant shrew in postgrazing environments in eastern Oregon.

Other species of small mammals were either trapped or observed on the Summit Creek study site. The Great Basin pocket mouse, a species that generally occurs in arid and semiarid habitats (Verts and Kirkland 1988), was trapped only on the ungrazed plot (table 3). It was caught at a single location in the sagebrush/upland community type where giant wildrye (*Elymus cinereus*) was codominant with scattered individuals of sagebrush and rabbitbrush. Mounds of the northern pocket gopher were evident throughout the area, but it was trapped only in the ungrazed habitat. Columbian ground squirrels (*Spermophilus columbianus*) were occasionally seen on the study area, especially early in the season. Mink (*Mustela vison*) and muskrats (*Ondatra zibethicus*) were rarely observed and only in the ungrazed habitat.

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APPENDIX: BIRDS AND MAMMALS OBSERVED ON OR OVER GRAZED AND UNGRAZED STUDY PLOTS, SUMMIT CREEK, ID, 1989

Birds

Great blue heron	*Ardea herodias*
Canada goose	*Branta canadensis*
Green-winged teal	*Anas crecca*
Mallard	*Anas platyrhynchos*
Northern pintail	*Anas acuta*
Cinnamon teal	*Anas cyanoptera*
American wigeon	*Anas americana*
Lesser scaup	*Aythya affinis*
Northern harrier	*Circus cyaneus*
Red-tailed hawk	*Buteo jamaicensis*
American kestrel	*Falco sparverius*
Sandhill crane	*Grus canadensis*
Killdeer	*Charadrius vociferus*
Willet	*Catoptrophorus semipalmatus*
Spotted sandpiper	*Actitis macularia*
Long-billed curlew	*Numenius americanus*
Wilson's phalarope	*Phalaropus tricolor*
Mourning dove	*Zenaida macroura*
Horned lark	*Eremophila alpestris*
Violet-green swallow	*Tachycineta thalassina*
Northern rough-winged swallow	*Stelgidopteryx serripennis*
Cliff swallow	*Hirundo pyrrhonota*
Barn swallow	*Hirundo rustica*
Black-billed magpie	*Pica pica*
Common raven	*Corvus corax*
Loggerhead shrike	*Lanius ludovicianus*
European starling	*Sturnus vulgaris*
Vesper sparrow	*Pooecetes gramineus*
Savannah sparrow	*Passerculus sandwichensis*
Red-winged blackbird	*Agelaius phoeniceus*
Western meadowlark	*Sturnella neglecta*
Yellow-headed blackbird	*Xanthocephalus xanthocephalus*
Brewer's blackbird	*Euphagus cyanocephalus*
Brown-head cowbird	*Molothrus ater*

Mammals

Vagrant shrew	*Sorex vagrans*
Water shrew	*Sorex palustris*
Columbian ground squirrel	*Spermophilus columbianus*
Northern pocket gopher	*Thomomys talpoides*
Great Basin pocket mouse	*Perognathus parvus*
Deer mouse	*Peromyscus maniculatus*
Montane vole	*Microtus montanus*
Muskrat	*Ondatra zibethicus*
Coyote	*Canis latrans*
Mink	*Mustela vison*
Pronghorn	*Antilocapra americana*

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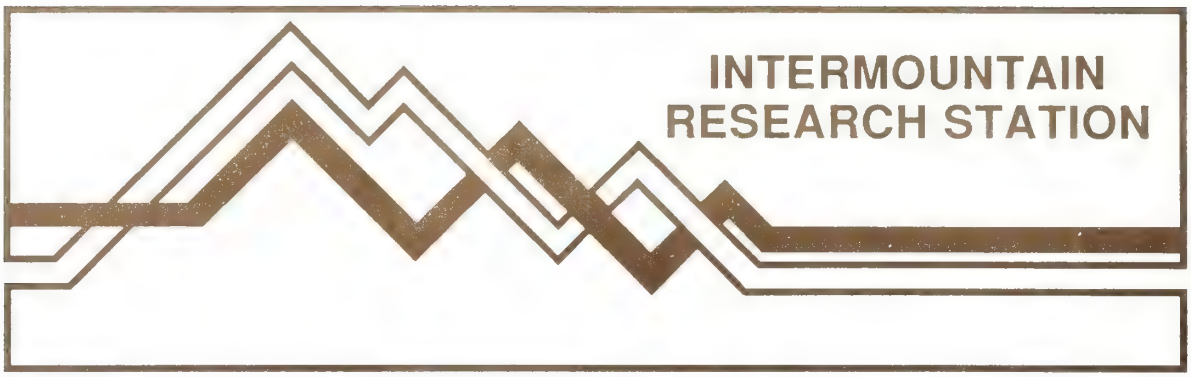
There was little difference between grazed and ungrazed habitats in total breeding bird density, but total bird biomass, bird species richness, and bird species diversity were 1.87, 1.75, and 1.62 times higher, respectively, in the grazed habitat. Small mammal populations were almost a third higher on the grazed area than on the ungrazed area.

KEYWORDS: density, diversity, biomass, nongame birds, shorebirds, rodents, shrews, rangeland, exclosure



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Greenhouse Evaluation of Reclamation Treatments for Perlite-Pumice Mine Spoils

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DEC

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RESEARCH SUMMARY

In greenhouse trials we studied the effects of three fertilizer levels and a surface straw mulch on the growth and development of two grass species, thickspike wheatgrass and Hycrest wheatgrass, grown in perlite ore, pumice ore, and perlite mill waste (a byproduct of pelite ore crushing and screening). These materials came from the National Perlite Products mine located in Oneida County in southeastern Idaho, and are representative of materials found in the area. The results show that fertilization is necessary for grass establishment and that increasing fertilizer rates result in significant ($p \leq 0.05$) increases in aboveground biomass (up to 45-fold), belowground biomass (up to twentyfold), number of culms (ninefold), and average leaf length (up to 80 percent) over no fertilizer levels. A surface mulch application equal to 2,200 kg/ha (2,000 lb/acre) produced a small but significant reduction in all the measured plant growth parameters. Due to low cation exchange capacity and low water-holding characteristics of these materials, incorporation of organic matter into the soil profile is recommended. The two grass species appear to be well suited for reclamation of these materials.

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INTRODUCTION

Surface mining presents resource managers with the challenging problem of establishing vegetation on large disturbances covered by mine spoils. These spoils usually have uncertain structure, low nutrient availability, and often phytotoxic compounds. This is especially true in the arid and semiarid West where limited rainfall during the growing season and high soil surface temperatures frequently limit plant establishment and growth. Considerable information has been accumulated over the past 15 years on techniques for revegetating spoils resulting from the surface mining of some of the more common commodities such as coal (Fisher 1983; Wali 1978), phosphates (Farmer and Blue 1978), copper, silver, and gold (Brown and Chambers 1989; Brown and others 1978; Johnston and others 1975) and drastically disturbed lands in general (Allen 1988; Schaller and Sutton 1978; Thames 1977; Wali 1975). Little is known, however, about the unique spoil properties that must be considered for establishment of vegetation on spoils of less common minerals such as perlite and pumice.

Recent expansion of open-pit mining activity for perlite and pumice in Oneida County of southeastern Idaho has raised questions regarding the feasibility of establishing stabilizing vegetation on the increasingly abundant spoil materials from such operations. Both perlite and pumice are a product of volcanism. Perlite is a glassy volcanic rock that has the unusual characteristic of expanding up to 20 times its original volume when appropriately heated. In its crude form it is essentially a metastable amorphous aluminum silicate that has a pH of approximately 7 and is chemically inert. In its expanded form it is used for a wide variety of products such as noncombustible insulation, soil conditioner, acoustical plaster, a filter to purify liquids, and as an inert carrier for pesticides. Pumice is essentially an aluminum silicate with a cellular structure formed by a process of explosive volcanism. Pumice also has a variety of commercial uses and is valued primarily as a lightweight concrete aggregate and as an abrasive for cleaning and scouring compounds (cover photo).

Of initial concern was the suitability of the spoil material for supporting vegetation growth. We conducted chemical analyses on three different spoil materials to determine nutrient limitations, followed by a greenhouse study during the winter of 1987-88. The primary objective was to determine the effects of standard reclamation techniques of fertilization and mulching on plant growth responses in perlite and pumice spoils. Additionally, we compared the performance of a native rhizomatous grass growing on the site and a drought-resistant introduced grass similar to that commonly used for range revegetation in the area.

METHODS

Three types of spoil material were examined: (1) pumice ore, (2) perlite ore, and (3) perlite mill waste consisting of impurities and undersized materials resulting from the crushing and screening of perlite ore. Preliminary soil analyses from duplicate grab-samples of each of the three spoil types provided the basis for determining nutrient additives to be tested in the greenhouse. The results of these analyses (table 1) indicated a general need for additions of nitrogen (N), phosphorus (P), potassium (K), and sulfur (S) to raise the fertility to a level suitable for the growth of grasses. We tested the growth potential of each of the three spoil types with three fertilization treatments: (1) a high rate consisting of 67 kg/ha (60 lb/acre) of N, 34 kg/ha (30 lb/acre) of P, 45 kg/ha (40 lb/acre) of K, 11 kg/ha (10 lb/acre) of iron (Fe) and 100 kg/ha (90 lb/acre) of S; (2) a low rate of one-half of the above rate for each nutrient; and (3) no fertilization. Nitrogen was added in the form of ammonium sulfate, P was applied as superphosphate, K was applied as potassium chloride, Fe was applied as iron sulfate, and the S application was calculated from the sulfur component of the other fertilizers. In addition, tests were run with and without surface mulching. Half the pots were mulched with straw at an equivalent rate of 2,200 kg/ha (2,000 lb/acre) to ameliorate the high soil surface temperatures and to reduce evaporation. Mulch would typically be applied in a field reclamation situation to prevent surface erosion and seed displacement. Thus, it was desirable to see how mulching would effect first year soil fertility and plant growth.

Two grass species of different growth forms were used in the greenhouse trial: (1) thickspike wheatgrass (*Agropyron dasystachyum* [Hook.]), a rhizomatous grass native to the area, and (2) Hycrest wheatgrass (*Agropyron cristatum* [L.] Gaertner X *Agropyron desertorum* [Fischer ex Link] Schultes), a recently developed tussocked hybrid

Table 1—Initial soil analyses for the three different spoil materials used in the growth tests

Element/characteristic	Perlite ore	Pumice ore	Perlite mill waste
Organic matter (percent)	[1]0.3	0.1	0.4
Soil pH	8.6	8.4	7.0
Bicarbonate P (mg/kg)	6	4.6	6.4
Potassium (mg/kg)	70	42	68
Magnesium (mg/kg)	87	34	66
Calcium (mg/kg)	1,090	893	558
Nitrate (mg/kg)	6	4	4
Sulfur (mg/kg)	13	4	5
Zinc (mg/kg)	27.9	1.2	1.4
Hydrogen (meq/100 g)	0.0	0.0	0.0
Cation exchange capacities (meq/100 g)	6.4	2.2	3.5
Percent base saturation:			
K (percent)	2.8	5.0	5.0
Mg (percent)	11.4	13.3	15.6
Ca (percent)	85.8	81.7	79.4
H (percent)	0.0	0.0	0.0
Soil separates:			
Sand (percent)	82	83	84
Silt (percent)	13	13	9
Clay (percent)	5	4	7

[1]Values are means; $n = 3$.

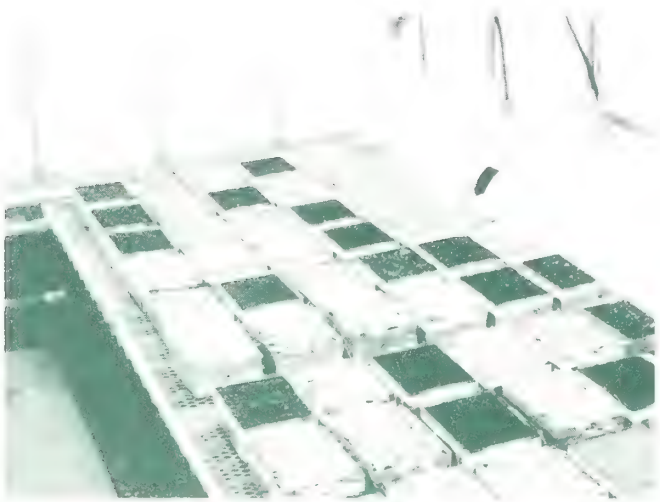


Figure 1—Greenhouse study design layout; dark-colored material is mill waste, light gray material is pumice or perlite. Straw mulch covers the surface on one-half of the pots.

with relatively good growth and drought-tolerance characteristics (Asay and Knowles 1985). Each species was planted in separate rectangular pots containing combinations of spoil type, fertilizer level, and presence or absence of mulch. The individual pots were of 19 by 27 cm (7.5 by 11 inches) surface dimension, and were filled to a depth of approximately 14 cm (5.5 inches). Several seeds were planted in six evenly spaced locations in each pot, and upon germination thinned to a single established individual at each of these six locations. There were three replications for each treatment.

The study design consisted of a randomized block test containing three blocks, three spoil materials, three fertilizer levels, two mulch conditions, and two species ($n = 108$) randomly distributed within each block (fig. 1). All test pots were maintained at a high level of available water adequate for plant growth.

At the end of a 110-day growth period, the following plant characteristics were measured: number of grass culms, culm length, aboveground biomass, and belowground biomass. In addition, chemical analyses were obtained for the spoil material in the pots (table 2) and of the aboveground plant tissue to obtain total nutrient uptake (AOAC 1984).

The data were analyzed by analysis of variance ($p \leq 0.05$) and mean comparisons with Fisher's protected least significant differences (Steel and Torrie 1980).

Table 2—Methods of soil analysis

Soil property	Method
pH	Glass electrode in a 1:1 slurry of soil and distilled water (McLean 1980)
OM (percent)	Chromic acid digestion with colormetric determination (Walkley and Black 1934, as modified by Schulte 1980)
NO_3 (mg/kg)	Specific ion electrode in a saturated calcium sulfate extraction (Carson 1980a)
P (mg/kg)	Extraction with 0.5M $NaHCO_3$ at pH of 8.5 (Olsen and others 1954)
K, Mg, Ca, Na (mg/kg)	Flame photometry of a 1 soil:5, 1N ammonium acetate extraction (Carson 1980b; Doll and Lucas 1973)
Na (mg/kg)	Flame photometery of a 1N ammonium acetate extraction (American Society of Agronomy 1982)
Zn (mg/kg)	DTPA extraction (Lindsay and Norvell 1978; Whitney 1980)
Texture (percent)	Hydrometer method of particle size analysis (Day 1973)

RESULTS

As expected, the amount of fertilization substantially and progressively increased the growth of both grasses. The unfertilized spoil material, regardless of origin, marginally supported plant growth, whereas the heavily fertilized spoils supported substantial growth (fig. 2). The differences among all three levels of fertilizer application were statistically significant for all plant growth characteristics measured: aboveground biomass production, belowground biomass production, number of grass culms, and culm length (table 3). Overall, the low level of fertilization produced approximately a 25-fold increase in aboveground production, a fifteenfold increase in belowground production, a sevenfold increase in number of grass culms, and 60 percent increase in the length of culms, compared to untreated spoils. The high level of fertilization produced approximately a 45-fold increase in aboveground production, a twentyfold increase in belowground production, a ninefold increase in number of culms, and about an 80 percent increase in culm length compared to untreated spoils. Doubling the amount of fertilizer from 33 to 66 kg/ha increased aboveground biomass by 69 percent, increased belowground biomass by 36 percent, increased the number of grass culms by 38 percent, and increased the length of culms by 11 percent.

Aboveground biomass production was least for grasses grown on the perlite ore compared to the other two substrates (table 3). Although the initial soil analyses (table 1) indicated that perlite ore had at least as good a fertility status as the other two substrates, soil analyses following completion of the experiment showed a depletion of nitrate (NO_3) in the perlite ore (table 4). Neither culm length nor number of culms differed significantly among the various spoil materials.

The mulch treatment had an opposite effect to that anticipated, in that mulching slightly inhibited plant growth in this greenhouse trial. Both above- and belowground biomass, as well as numbers of culms, were significantly lower in the mulched pots (table 3). Apparently the use of mulch for reducing plant water stress under the nonstressful greenhouse conditions was offset by the detrimental effect of surface heat trapping by the mulch (Cochran 1969), or possibly by creating a C:N imbalance.

The two wheatgrasses generally responded similarly on the different spoil materials and to the different amendments. Thickspike wheatgrass, however, produced slightly more culms and somewhat lower belowground biomass than Hycrest wheatgrass (table 3). These differences, although statistically significant, were not reflected by the other growth measurements.

A significant interaction occurred between the type of spoil material and the level of fertilization for aboveground biomass, belowground biomass, and number of culms (fig. 3). The perlite mill waste produced significantly more aboveground biomass with low fertilization than either the perlite or pumice ore, and both the perlite mill waste and pumice ore produced more biomass with high fertilization than did the perlite ore. At both low and

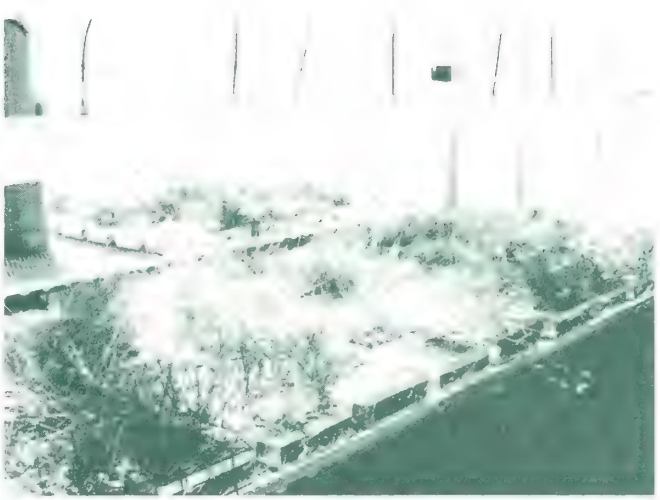


Figure 2—Grass development near the end of the assessment period; notice the nonfertilized pots located in the foreground near center of the bench.

Table 3—Significant effects ($p \leq 0.05$) of different spoil materials and different treatments on plant growth characteristics. Means in the same row followed by different letters differ significantly

Plant characteristic	Spoil material		
	Perlite	Pumice	Perlite mill waste
Aboveground production (g/pot)	5.66 A	7.36 B	7.71 B
Belowground production (g/pot)	9.08 A	11.26 B	8.56 A
	Fertilization		
	None	**Low**	**High**
Aboveground production (g/pot)	0.28 A	7.61 B	12.84 C
Belowground production (g/pot)	.77 A	11.94 B	16.19 C
Number of culms (No./pot)	14.5 A	96.4 B	133.0 C
Average culm length (mm)	114. A	184. B	204. C
	Mulch		
	Yes		**No**
Aboveground production (g/pot)	6.48 A		7.34 B
Belowground production (g/pot)	8.85 A		10.42 B
Number of culms (No./pot)	76.6 A		86.0 B
	Grass type		
	Thickspike wheatgrass		**Hycrest wheatgrass**
Belowground production (g/pot)	8.38 A		10.88 B
Number of culms (No./pot)	87.5 A		75.1 B

Table 4—Significant effects ($p \leq 0.05$) of different spoil materials and fertilizer levels on soil nutrient status following 110 days of plant growth. Means in the same row followed by different letters differ significantly

Soil characteristic	Perlite		Pumice		Perlite mill waste	
	No fertilization	High fertilization	No fertilization	High fertilization	No fertilization	High fertilization
Soil pH	8.7 A	8.3 A	8.7 A	7.5 B	8.2 A	6.7 C
Nitrate (mg/kg)	6.2 A	3.8 B	10.3 C	5.2 AB	8.3 C	5.3 AB
Bicarbonate P (mg/kg)	5.8 A	11.8 B	5.0 A	10.6 BC	5.8 A	9.6 C
Potassium (mg/kg)	80.8 A	69.6 B	52.2 C	45.4 C	72.0 B	61.5 D
Magnesium (mg/kg)	90.7 A	82.2 B	42.2 C	46.3 C	75.0 D	76.0 D
Calcium (mg/kg)	1,158.0 A	1,118.0 B	357.0 C	338.0 C	597.0 D	534.0 E
Sodium (mg/kg)	23.7 A	23.0 B	22.4 B	18.5 CD	21.2 BC	16.8 D
CEC (meq/100 g)	6.8 A	6.6 A	2.4 B	2.3 B	3.9 C	3.6 C

high fertilization levels, the pumice ore produced significantly more belowground biomass than either the perlite ore or perlite mill waste. No significant differences in belowground biomass production were noted for the unfertilized treatment. With no fertilization the perlite mill waste produced a significantly greater number of grass culms than either the perlite ore or the pumice ore. In the two fertilizer treatments, culm production among the substrate types was almost identical.

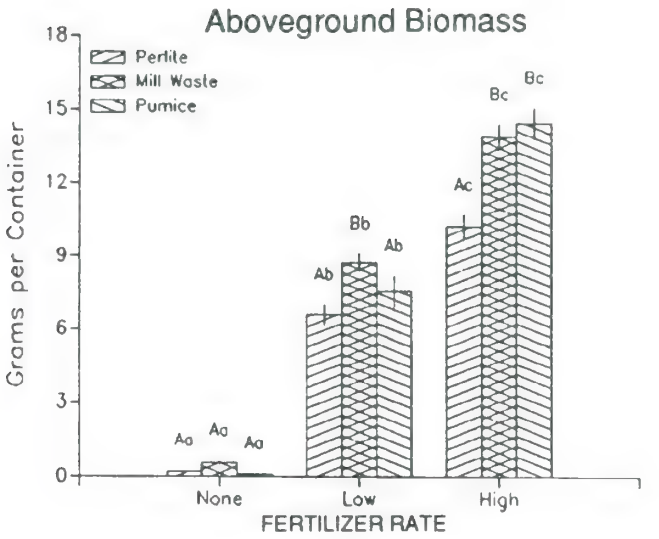
Plant nutrient uptake for the unfertilized and high fertilizer treatments paralleled biomass production. The 45-fold difference between the zero and high fertilizer levels for aboveground biomass production was reflected in an average 46-fold greater uptake of N, a 45-fold greater uptake of P, a 55-fold difference in K, and a thirtyfold difference in Ca (table 5). In general the two wheatgrasses did not differ significantly in the amount of nutrient uptake. Total elemental uptake was significantly higher in those plants growing in the fertilized versus nonfertilized pots. Generally, plant nutrient uptake was significantly lower from the perlite ore than from either the pumice ore or the perlite mill waste (table 6). This again paralleled the smaller amount of biomass production from the perlite ore versus the other two spoil materials. The exceptions were magnesium (Mg), calcium (Ca), aluminum (Al), and zinc (Zn), which did not differ significantly among the different spoil materials. Plant uptake of sodium (Na) was significantly higher from the perlite ore than from the other materials.

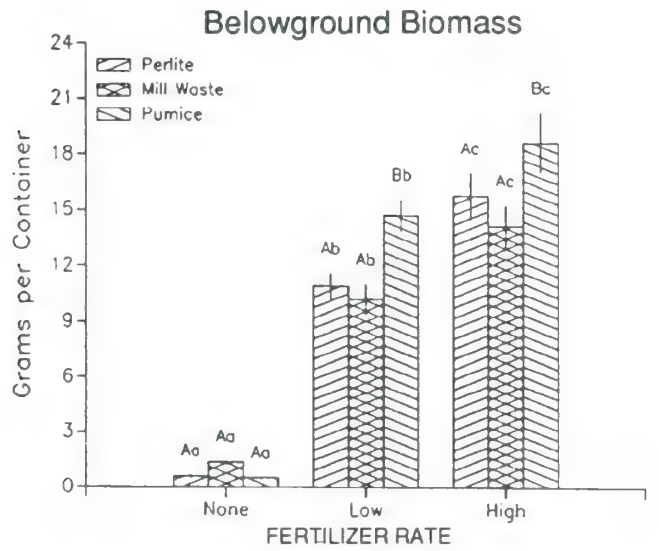
Soil nutrient analyses at the end of the 110-day plant growth period revealed differences in nutrient concentrations remaining in the different spoil materials with and without fertilization (table 4). With the exception of bicarbonate phosphorus, significantly more of all of the nutrients examined were extracted by the plants growing in the fertilized than in the nonfertilized spoils. A difference also was observed among soil types. Neither the presence of mulch nor the type of wheatgrass growing on the spoil material significantly affected the amount of remaining nutrients. High fertilization significantly reduced the pH level on both the pumice ore (from 8.7 to 7.5) and perlite mill waste (from 8.2 to 6.7), but not on the perlite ore. In most cases there was significantly less NO_3, K, Ca, and Na present in the fertilized than in the nonfertilized spoil materials. The lower amount of these elements in the fertilized spoils can be explained by differences in plant growth. The comparatively large amount of root growth in the fertilized spoils fully occupied the pots and permitted nutrient extraction from the entire pot volume. This was not true of the unfertilized pots, which had very limited root growth confined to the upper portion of the pots. As a consequence, this limited root distribution was unable to extract nutrients from the entire pot volume.

Interestingly, the data suggest that the amount of K, Mg, Ca, and NO_3 in the unfertilized spoils (table 4) was somewhat higher than these nutrient levels prior to the start of plant growth (table 1). Theoretically, the levels should be less. We were unable to test the statistical significance of the differences because of the limited sample of spoil nutrients before plant growth. The discrepancy is believed to result from the limited number and variability of pregrowth samples.

CONCLUSIONS AND RECOMMENDATIONS

Perlite ore, pumice ore, and perlite mill waste do not contain sufficient nutrients to support the establishment and growth of vegetation needed for adequate revegetation. Initial soil analyses indicated deficiencies of all macronutrients on all three substrates. Although we did not test for all micronutrients, tests for S and Zn were also low. A single application of 33 kg/ha (30 lb/acre) of N (as ammonium sulfate), 17 kg/ha (15 lb/acre) of P (as superphosphate), 22 kg/ha (20 lb/acre) of K (as potassium chloride), and 6 kg/ha (5 lb/acre) of Fe (as iron sulfate) will increase the nutrient level sufficiently to enable the establishment of vegetation cover. Doubling the amount of fertilizer will increase the amount of above- and belowground plant biomass substantially. If the intent, however, is to return areas to a native grass/shrub cover, the lower rate of fertilization may be the most appropriate (Chambers 1989). Because of the coarse texture of these spoil materials and their low cation exchange capacities,





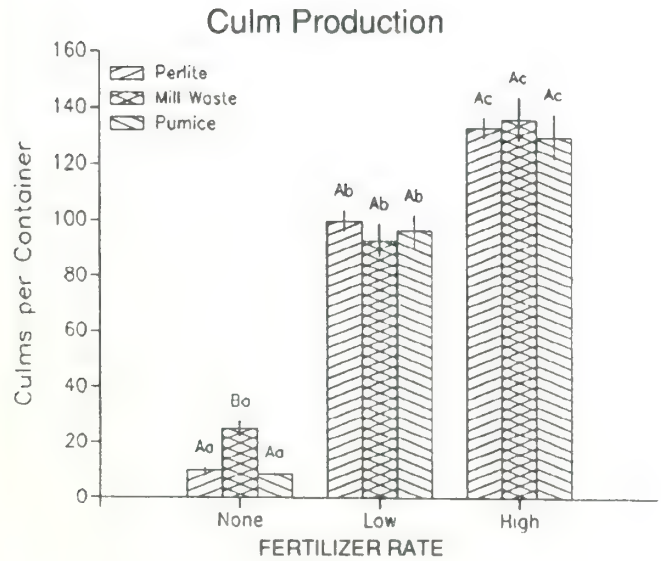


Table 5—Nutrient uptake (micrograms/pot) by aboveground plant tissue of thickspike and Hycrest wheatgrasses following 110 days of growth on the nonmulched pots, with two levels of fertilization. Means in the same row followed by different letters differ significantly ($p \leq 0.05$)

	No fertilization		High fertilization	
Element	**Thickspike**	**Hycrest**	**Thickspike**	**Hycrest**
Nitrogen	3.19 A	3.37 A	152.86 B	149.96 B
Phosphorus	.65 A	.61 A	28.62 B	27.76 B
Potassium	3.39 A	3.82 A	200.67 B	197.51 B
Sulfur	.41 A	.46 A	19.34 B	21.44 B
Magnesium	.68 A	.61 A	18.82 B	17.37 B
Calcium	1.86 A	2.01 A	56.95 B	60.07 B
Sodium	.06 A	.07 A	.97 B	1.21 C
Iron	.02 A	.02 A	.71 B	.64 B
Aluminum	.02 A	.02 A	.61 C	.48 B
Manganese	.01 A	.02 A	.74 B	.91 C
Boron	<.01 A	<.01 A	.09 B	.10 B
Copper	<.01 A	<.01 A	.07 B	.07 B
Zinc	.02 A	.02 A	.96 C	.45 B

Table 6—Significant effects ($p \leq 0.05$) of different spoil materials on nutrient uptake (micrograms/pot) by aboveground plant tissue following 110 days of growth. Means in the same row followed by different letters differ significantly

Nutrients/ elements	**Perlite**	**Pumice**	**Perlite mill waste**
Nitrogen	71.6 A	106.1 B	98.7 B
Phosphorus	11.6 A	20.1 B	19.7 B
Potassium	97.0 A	128.7 B	137.0 B
Sulfur	9.0 A	13.6 B	14.6 B
Sodium	1.04 B	.56 A	.44 A
Iron	.29 A	.47 B	.48 B
Manganese	.14 A	.57 B	.80 C
Boron	.05 A	.07 C	.06 B
Copper	.03 A	.05 B	.05 B

Figure 3—Significant effects ($p \leq 0.05$) of three spoil materials and three fertilizer rates on aboveground biomass, belowground biomass, and culm production. Differences between means are indicated by upper-case letters for spoil materials and by lower-case letters for fertilizer rates. Comparison of spoil materials is within fertilizer groups while fertilizer rate comparison is associated with identical spoil materials.

several light applications of fertilizer applied at about 2-year intervals may be more beneficial than a single larger application at the time of seeding (Tisdale and Nelson 1975).

Application of a surface straw mulch under nonstressful greenhouse conditions inhibited plant growth, possibly because of the negative effects of surface heat trapping or by creating an imbalance of the C:N ratio. Under stressful field conditions, however, we believe that mulching should have an overall beneficial effect on plant establishment and growth by reducing evaporation and by preventing soil erosion and seed displacement. Actually incorporating organic matter into the substrate, particularly with the addition of N, should facilitate microbial activity, induce development of a relatively complete soil biota, and result in higher rates of substrate decomposition and mineralization (Woods and Schuman 1986). Crimping straw or meadow hay into the soil surface can provide similar benefits attributed to both surface mulching and mulch incorporation.

The native rhizomatous grass (thickspike wheatgrass) and the introduced tussock hybrid (Hycrest wheatgrass) performed equally well in the greenhouse trials and appear well suited for revegetating the fertilized and mulched substrate from all three spoil materials. As a general practice, species for reclamation should be selected from native species growing on or near the area, or from introduced species on the basis of their ability to perform well under the climatic and edaphic conditions on the site. The planting of native or adapted introduced legumes could have the added benefit of not only providing N for their own needs but may provide some excess for other plants as well.

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Thickspike wheatgrass and Hycrest wheatgrass were grown in perlite ore, pumice ore, and perlite mill waste from a mine in southeastern Idaho. Results show that fertilization is necessary for grass establishment and that increasing fertilizer significantly ($p \leq 0.05$) increases aboveground biomass (up to 45-fold), belowground biomass (up to twentyfold), number of culms (ninefold), and average leaf length (up to 80 percent) over no fertilizer. Mulch equal to 2,200 kg/ha (2,000 lb/acre) significantly reduced all plant growth parameters.

KEYWORDS: *Agropyron dasystachyum*, *Agropyron cristatum* x *Agropyron desertorum*, perlite, pumice, revegetation

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Differences in Vegetation Biomass and Structure Due to Cattle Grazing in a Northern Nevada Riparian Ecosystem

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RESEARCH SUMMARY

Plant biomass and structure on an area seasonally grazed by cattle was compared to that on a comparable adjoining area fenced from grazing for the previous 11 years. The study was on the West Fork of Deer Creek in northeastern Nevada. Differences between the grazed and ungrazed situations were compared for the riparian plant community complex—aspen (*Populus tremuloides*)/willow (*Salix* spp.)/Kentucky bluegrass (*Poa pratensis*)—and for the adjacent steep upland community—big sagebrush (*Artemisia tridentata*)/upland. Less graminoid biomass and height, but more nonwillow large shrub biomass and more soil compaction were the most obvious effects of cattle grazing within the riparian plant community complex. Relatively little grazing of the adjacent upland occurred, and few grazing effects were measured. Aspen stands were relatively similar on the grazed and the ungrazed areas, implying that recent levels of grazing have not greatly affected aspen regeneration. On an adjacent supplemental study area, very heavy grazing had a major impact on aspen regeneration and stand structure. Most of the plant biomass across the entire study area was contributed by down, dead aspen drowned by flooding from a series of now-abandoned beaver dams.

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INTRODUCTION

Riparian areas in western North America are generally associated with drainage courses and thus are usually elongate. Water, nutrients, sediments, and organic matter tend to concentrate in the riparian areas (Coston and others 1978). These elements permit development of plant communities that are more diverse and more productive than those of surrounding uplands. Though small in aggregate area, riparian areas serve as islands of diversity in regional landscapes. Plant communities within riparian areas are often arranged in complex mosaics associated with soil and hydrologic variation (Thomas and others 1979; Tuhy and Jensen 1982).

Riparian ecosystems have certain attributes that constitute important wildlife habitat (Thomas and others 1979). Water, food, and cover in close proximity and in kinds and amounts not found nearby produce relatively high densities and diversities of animal species (Carothers and others 1974; Compton and others 1988; Hubbard 1977). The vegetation along small and intermediate-sized streams helps control physical conditions in the stream environment. The roots stabilize streambanks, retard erosion, and influence bank morphology while aboveground vegetation slows highwater streamflow and sediment and detritus movement, and is a source of large organic debris for streams (Jahn 1978; Meehan and others 1977).

Given the opportunity, most domestic livestock, such as cattle, will spend a disproportionate amount of time in riparian areas as compared to adjacent xeric upland areas. The time spent may be five to 30 times longer than expected based on extent of the riparian area. This often leads to overgrazing of the riparian community (Skovlin 1984). Reductions of riparian herbage standing crop by grazing livestock vary greatly. Platts (1982) reported that herded sheep may reduce herbage in the riparian area by only a negligible amount. The amount of herbage removed by cattle may be in the moderate range on high mountain meadows (interpreted from Platts and Nelson 1986) to nearly 100 percent in a riparian area transecting the semiarid big sagebrush zone (Platts and Nelson 1984). Severe overgrazing is almost invariably detrimental to herbaceous and woody plant communities, but only limited information is available concerning the effects of well-managed grazing on riparian plant communities (Clary and Webster 1989).

Dramatic vegetation successional changes can occur when the grazing stress is removed. If habitat deterioration is not severe, herbaceous vegetation can greatly increase within several growing seasons (Platts and Nelson 1984), and woody vegetation can rebound within 5 to 10 years (Rickard and Cushing 1982; Skovlin 1984). But severe habitat deterioration can require very long recovery times, perhaps decades (Knopf and Cannon 1982) or more (Platts and Raleigh 1984).

Studies conducted on Deer Creek in northern Nevada have previously shown that grazing at a moderate to heavy rate, although not at an extreme rate, resulted in no change in nesting bird populations but did result in a reduction of small mammal populations as compared to an ungrazed exclosure (Medin and Clary 1989 and in preparation). Fish populations in the same area were little different from the ungrazed exclosure, although certain fishery habitat characteristics had been changed by the grazing (Contor and others 1989; Crispin 1981; General Accounting Office 1988).

For a similar area on Deer Creek as reported in the studies above, this paper documents the vegetation characteristics of the grazed and ungrazed riparian community complex (Winward and Padgett 1989) and an adjacent xeric sagebrush community. An additional supplemental study of aspen stand characteristics was made on a nearby area annually subjected to very heavy grazing.

STUDY AREA

The study area is on the West Fork of Deer Creek in northeastern Nevada. The Deer Creek site is at an elevation of approximately 1,890 m, 55 km north of Wells, NV. The small stream originates from springs and flows in a narrow, V-shaped canyon cut into mid-Tertiary rhyolitic rock. Average gradient of the canyon bottom is 2 to 3 percent. Soils are generally fine-textured, ranging from shallow on steep residual slopes to very deep on relatively level alluvial fans and floodplains (Platts and others 1988). The riparian areas seldom exceed 25 to 50 m in width.

The stream was closely bordered by clumped stands of aspen, willow, and other deciduous shrubs—primarily currant (*Ribes* spp.), Woods rose (*Rosa woodsii*), and snowberry (*Symphoricarpos* spp.). The gallerylike riparian area appeared as an island surrounded by an upland

plant community dominated by big sagebrush but also included rubber rabbitbrush (*Chrysothamnus nauseosus*) and antelope bitterbrush (*Purshia tridentata*).

The herbaceous component within the riparian complex included Kentucky bluegrass, bluebunch wheatgrass (*Agropyron spicatum*), slender wheatgrass (*A. trachycaulum*), sedge (*Carex* spp.), mannagrass (*Glyceria* spp.), Baltic rush (*Juncus balticus*), horsetail (*Equisetum arvense*), common yarrow (*Achillea millefolium*), aster (*Aster* spp.), yellow sweetclover (*Melilotus officinalis*), clover (*Trifolium* spp.), and lupine (*Lupinus* spp.). Typical species on the adjacent upland are bluebunch wheatgrass, Sandberg's bluegrass (*Poa secunda*), cheatgrass (*Bromus tectorum*), Indian paintbrush (*Castilleja* spp.), balsamroot (*Balsamorhiza* spp.), and wild buckwheat (*Eriogonum* spp.).

Narrow floodplains with dead and downed aspen are common in the study area. These remnants of aspen communities were once flooded by beaver impoundments that drowned the trees. Numerous washed-out dams are evident, but beaver no longer inhabit the study area.

Eight major and several minor vegetation community types have been identified in the Deer Creek riparian area and adjoining upland (Platts and others 1988). The big sagebrush (*Artemisia tridentata*)/upland type occupied the steep canyon slopes. The remaining types were considered as components of a riparian complex typified by aspen (*Populus tremuloides*), willow (*Salix* spp.), and Kentucky bluegrass (*Poa pratensis*). A riparian complex represents a unit of land that supports or may potentially support a similar grouping of community types (Winward and Padgett 1989). A formal description and designation of the riparian complex(es) on Deer Creek was beyond the scope of this investigation.

The primary study was conducted within a large (40+ ha) cattle exclosure, fenced 11 years previously (trespass grazing did occur on several occasions) and on an adjacent area selected on the basis of topographical and vegetational similarities with the enclosed area. The construction of the exclosure across the narrow Deer Creek canyon served as a drift-fence reducing the cattle use of the grazed portion of the primary study area (upstream side of the exclosure), as compared to previous years. Grazing on a supplemental study area immediately downstream from the exclosure has continued to be very heavy (approximately 90 percent herbage removal).

These public lands, managed by the Bureau of Land Management, are usually grazed from about mid-August to mid-November. Because of weather conditions, grazing in the year of study was mid-July to mid-October (Phillips and Marteney 1989).

METHODS

The rectangular cattle exclosure, about 965 m long and of variable width, is oriented lengthwise along the West Fork. Two 600- by 150-m plots, one in the upper section of the exclosure and the other in the adjoining (upstream) grazed area, were sampled for vegetation and other characteristics from August 15 to September 2, 1988. For each of the grazed and ungrazed situations, the riparian complex contained 60 sample locations, and the adjacent steep upland site contained 12 sample locations. A 50- by 50-cm (0.25-m^2) quadrat was located at each of the systematically positioned sample locations. Canopy cover (Daubenmire 1959) was ocularly estimated for the total of each plant life form (graminoid, forb, shrub) and recorded in percentage as the midpoint of one of eight cover classes (0-1, 1-5, 5-10, 10-25, 25-50, 50-75, 75-95, 95-100). Percentages of litter, rock, bare ground, and lichen-moss were similarly estimated. The vegetative height (excluding flower and seedhead heights) of each graminoid, forb, and shrub nearest the center of each quadrat was recorded.

Biomass of graminoids, forbs, and small shrubs was determined by clipping vegetation from ground level upward within a vertical projection from the 0.25-m^2 quadrats. Clipped materials were bagged, ovendried, and weighed. A 3- by 3-m (9-m^2) plot, concentric to each 0.25-m^2 quadrat, was used to sample biomass of large shrubs. Basal diameter, maximum height, and species were recorded for each shrub stem rooted within the plot. For willow clumps, average stem diameter and average stem height were recorded instead of individual stems. Biomass of willows, bitterbrush, rose, currant, snowberry, oceanspray (*Holodiscus dumosus*), and serviceberry (*Amelanchier alnifolia*) was estimated by use of the equations of Brown (1976). Height and diameter at breast height (d.b.h.) were recorded for each tree stem rooted within 10- by 10-m (100-m^2) plots concentric to each 0.25-m^2 quadrat. Biomass of aspen was estimated by the Chicken Creek equations of Bartos and Johnson (1978).

Biomass of downed woody material was sampled midway between the vegetation sample locations. The methodology used was similar to Brown (1974) except that there were no corrections for slope and no measures of fine litter and duff. Samples of downed woody material were collected for determination of moisture content. All biomass data in this study are reported as grams per square meter ovendry.

Unconfined soil compressive strength (index of bulk density) was measured in opposing corners of the 0.25-m^2 quadrats with a pocket penetrometer, averaged, and recorded. The corners were selected to best represent mineral soil, that is, soil surface not covered by heavy litter or duff, or rock. The readings were taken immediately upon selection of the sample location before plant sampling activities impacted the soil surface. On the supplemental study area all aspen stems were recorded by size class in two adjacent 40- by 40-m plots—one very heavily grazed and one within the downstream end of the cattle exclosure.

Differences between the two primary treatment areas were tested for significance by unpaired t-test.

RESULTS AND DISCUSSION

We look at four topics in our study results: herbaceous and shrub vegetation; aspen; overstory-understory relationships; and plant biomass distribution.

Herbaceous and Shrub Vegetation

Riparian Complex—The greatest differences between the primary grazed and fenced situations were in the graminoids, as expected because graminoids normally constitute the dominant portion of cattle diets. Grass standing crop biomass in the grazed situation was only

Table 1—Plant biomass—riparian community complex

Plant group	Biomass (g/m^2)						
	Grazed			Ungrazed			
	Live	Dead	Total	Live	Dead	Total	*P* (totals)[1]
Grass	74.5	23.7	98.2	131.3	65.1	196.4	<0.01
Forb	13.3	0	13.3	16.5	0.1	16.6	.20
Total herbage	87.7	23.7	111.5	147.8	65.2	213.0	<.01
Small shrub							
Foliage	18.6	—	18.6	13.8	—	13.8	.44
Wood	24.8	11.7	36.5	23.4	3.1	26.5	.43
Total	43.4	11.7	55.1	37.2	3.1	40.3	.42
Large shrub							
Willow							
Foliage	63.3	—	63.3	73.9	—	73.9	.74
Wood	646.8	9.8	656.6	1,810.9	5.6	1,816.5	.41
Total	710.1	9.8	719.9	1,884.8	5.6	1,890.4	.41
Nonwillow							
Foliage	128.1	—	128.1	6.2	—	6.2	.01
Wood	440.3	10.0	450.3	8.3	13.8	22.1	.06
Total	568.4	10.0	578.4	14.5	13.8	28.3	.04

[1] *P* of less than 0.10 was considered significant.

about 50 percent of that in the fenced situation (table 1). Likewise, vegetative grass heights differed significantly between the two treatments (table 2). The differences in grass biomass and heights seemed predominantly due to recent livestock grazing rather than to a basic difference in plant growth between the two areas. Forbs exhibited less difference in standing crop biomass and vegetative plant height than did the graminoids.

There were no significant differences in characteristics of small shrubs such as sagebrush between the grazed and fenced areas. There was, however, a large difference between the calculated means of the willow standing crop biomass, but the significance was masked by the extreme variation among samples. The biomass attributed to large shrubs other than willow (currant, rose, snowberry, and so forth) was significantly higher in the grazed situation. Although one cannot be sure whether this is a response to site or grazing differences, Elmore (1988) described currant as replacing willow and alder when water tables are lowered in response to grazing or other stresses on the stream channel. Presumably, the reverse may also be true, so that if water tables rise in response to reduced erosion stress and to narrowing of the stream channels, willows may replace currant or rose or other plants.

There was little difference in the number of species per plot between grazed and ungrazed situations; thus grazing has not measurably affected overall plant diversities. Nevertheless, the grazed herbaceous plant compositions appeared by observation to contain more Kentucky bluegrass in the riparian complex and more annuals in the upland compared to plant compositions in the fenced area. The ground cover characteristics were similar between the two areas except for slightly more bare soil where grazing had occurred. Soil strength readings were significantly different, indicating that the soils were more compacted on the grazed area. This characteristic could result in reduced plant growth and greater surface water flow, thereby creating a drier site and increased erosion potential (Branson and others 1981).

Adjacent Upland—As expected, the adjacent xeric steep upland sites received less grazing use than the riparian area (Myers 1989; Skovlin 1984). Few characteristics were significantly different between grazed and fenced situations, although some possible differences in mean values appeared in this relatively limited sample

Table 2—Ground cover and miscellaneous characteristics—riparian community complex

Item	Grazed	Ungrazed	*P*[1]
Cover (percent)			
Bare	9.6	5.6	0.08
Litter	25.2	29.5	.20
Rock	4.0	2.1	.22
Lichen-moss	.1	<.1	.58
Grass	54.7	56.0	.72
Forb	6.6	7.6	.54
Shrub	5.2	4.2	.59
Plant height (m)			
Grass	.25	.37	<.01
Forb	.12	.16	.06
Shrub	1.46	1.35	.61
Species per 0.25 m^2			
Grass	2.40	2.28	.30
Forb	1.37	1.60	.24
Shrub	.43	.33	.36
Soil compressive strength (kg/cm^2)	2.05	1.35	<.01

[1] *P* of less than 0.10 was considered significant.

Table 3—Plant biomass—*Artemesia tridentata*-upland community type

Plant group	Biomass (g/m^2)						
	Grazed			Ungrazed			
	Live	Dead	Total	Live	Dead	Total	*P* (totals)[1]
Grass	41.3	9.0	50.3	44.0	10.7	54.7	0.74
Forb	18.7	0	18.7	8.0	0	8.0	.25
Total herbage	60.0	9.0	69.0	52.0	10.7	62.7	.70
Small shrub							
Foliage	64.0	—	64.0	110.3	—	110.3	.48
Wood	44.7	156.0	200.7	200.7	50.3	251.0	.71
Total	108.7	156.0	264.7	311.0	50.3	361.3	.61
Large shrub							
Foliage	76.5	—	76.5	24.8	—	24.8	.14
Wood	612.3	17.3	629.6	241.2	T	241.2	.20
Total	688.8	17.3	706.1	266.0	T	266.0	.19

[1] *P* of less than 0.10 was considered significant.

of upland conditions (12 sample locations per grazing situation). Grass heights were significantly lower under grazing, but the standing crop biomass was not greatly different (tables 3, 4). Numbers of forb species were higher under grazing. This often occurs when grazing reduces the dominant species and allows a more diverse composition to develop (Dobson 1973).

Aspen

Although a grazing management change of only 11 years would not likely affect a stand of large mature aspen trees, it could cause a change in the young age classes of aspen. This is illustrated by data from the primary and the supplemental study areas (fig. 1). The plot grazed very heavily each year had mature and decadent aspen and a number of suppressed sprouts, the majority of which were less than 0.7 m high. However, the moderate to heavily grazed plot and the ungrazed plot in addition had impressive numbers of sapling-sized aspen (up to 9 cm d.b.h. and about 6.5 m tall), the largest of which were dated by tree-ring counts to the year of fence construction.

Removal of grazing normally results in an increase in aspen reproduction (DeByle 1985). The moderation of grazing on the primary grazed site, due to the barrier effect of the exclosure fence in the narrow canyon, appears to have also resulted in an increase in aspen reproduction although in somewhat reduced numbers as compared to the exclosure. These saplings should provide a basis for continuation of the aspen stand after the current mature trees senesce. The total lack of the sapling size class in the very heavily grazed area foretells the eventual loss of this aspen stand under current grazing practices.

Table 4—Ground cover and miscellaneous characteristics—*Artemesia tridentata*-upland community type

Item	Grazed	Ungrazed	*P*[1]
Cover (percent)			
Bare	21.9	34.8	0.18
Litter	12.2	8.9	.39
Rock	28.3	21.9	.62
Lichen-moss	0	0	—
Grass	23.0	23.2	.99
Forb	7.8	4.4	.45
Shrub	15.2	19.1	.63
Plant height (m)			
Grass	.19	.30	.04
Forb	.15	.16	.79
Shrub	.89	.66	.17
Species per 0.25 m^2			
Grass	1.67	1.58	.69
Forb	.83	.25	.03
Shrub	1.00	.75	.38
Soil compressive strength (kg/cm^2)	1.14	.78	.39

[1] *P* of less than 0.10 was considered significant.

Overstory-Understory Relationships

Aspen types are considered to be some of the best-suited vegetation types for joint production of wood and forage (Betters 1983). Overstory-understory relationships that portray the degree of plant competition can provide part of the basis for management strategies in these types. The overstory-understory relationships within the Deer Creek riparian complex appear to be weak, if indeed they exist at all. For instance, aspen density in the ungrazed area accounted for less than 1 percent of the variation in herbage biomass (fig. 2) and less than 2 percent of the variation in shrub biomass. Other research results conflict regarding aspen overstory and understory productivity relationships. Differences in understory plant response to different aspen sites may explain apparently divergent results (Betters 1983).

Because the relationships on Deer Creek are poorly defined, strong competition between plant life forms may

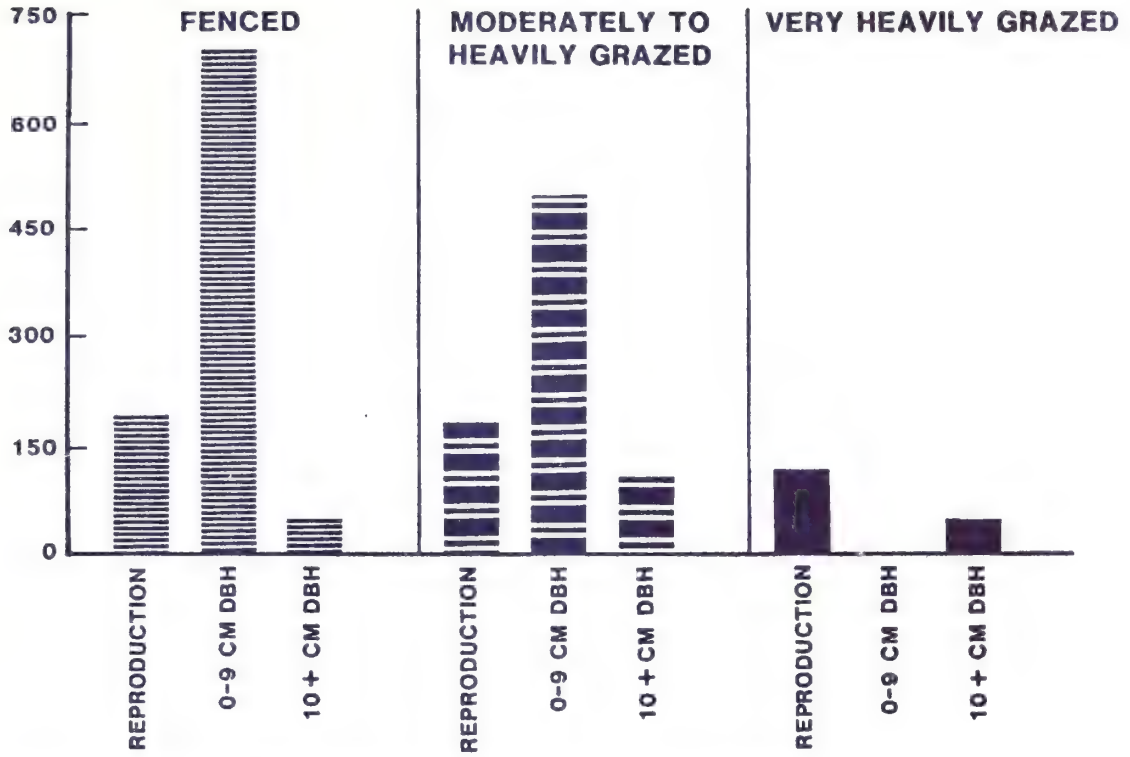

Figure 1—Number of aspen stems related to grazing intensity. Comparison is made between aspen communities within the fenced exclosure, the moderately to heavily grazed primary study area, and the very heavily grazed supplemental study area.

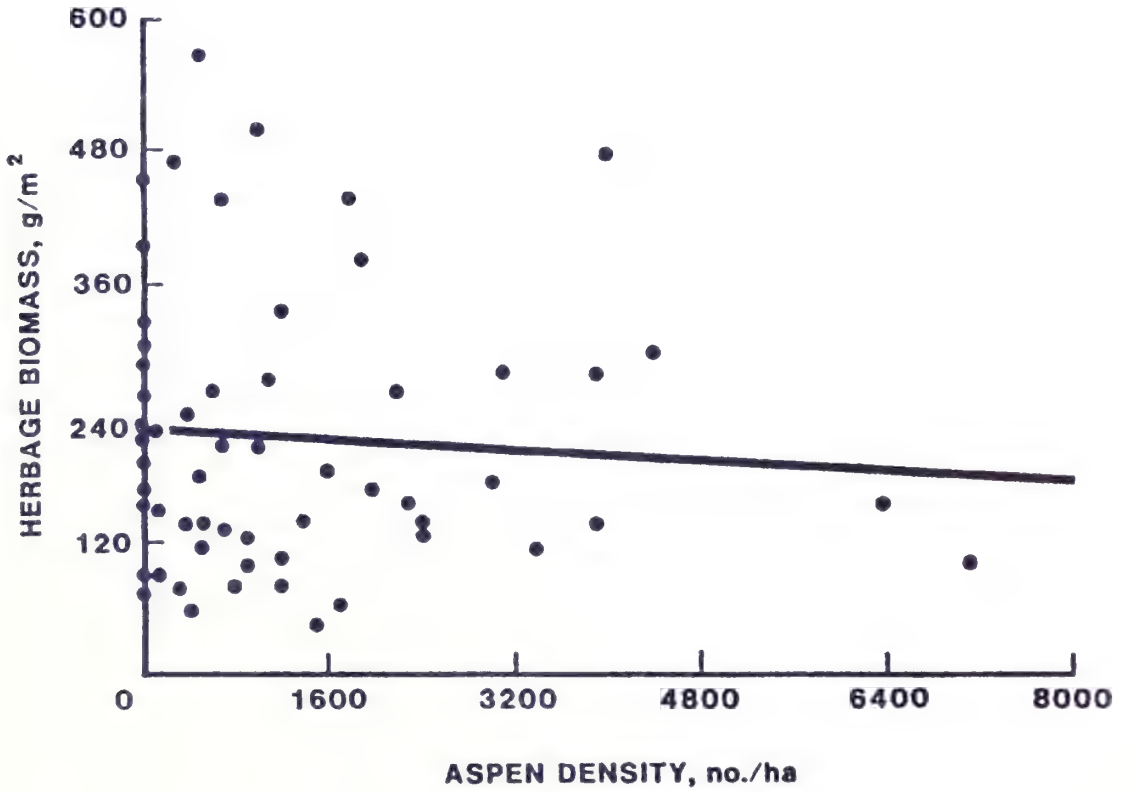

Figure 2—Relationship between herbage biomass and aspen density.

not exist in this riparian area. Medium-textured to fine-textured, deep to very deep soils, and access to a permanent water table may have greatly reduced competition between plant life forms compared to that typically occurring on semiarid and arid habitats (Ffolliott and Clary 1982). Some of the highest herbage biomass values occurred in conjunction with high amounts of willow biomass. A likely reason is the greater moisture availability in sites supporting willow communities (Platts and others 1988).

Plant Biomass Distribution

Figure 3 illustrates the distribution of biomass within the fenced riparian complex and adjacent steep upland on the West Fork Deer Creek study sites. Plant biomass within the riparian complex totaled 10,339.1 g/m^2. The live biomass made up 3,699.3 g/m^2, and of this 271.7 g/m^2 was foliage (nonwoody). Woody biomass, live and dead, constituted 97 percent of the total in this system. The average live aspen biomass, including large mature trees, was estimated to be 1,615.0 g/m^2. Standing dead aspen averaged 560.2 g/m^2, and downed woody biomass averaged 5,991.9 g/m^2. Dead biomass made up 64 percent of the total in the riparian complex.

The plant biomass in the fenced upland sites averaged 1,113.3 g/m^2. Foliage contributed 187.1 g/m^2, and the remainder was live and dead woody material. Down and dead aspen, which had fallen onto the lower portion of the upland sites from the riparian complex, contributed 423.3 g/m^2—38 percent of the total biomass and 87 percent of the dead biomass. Dead biomass was 44 percent of the total.

The amount of standing live biomass has undergone large changes in recent history, particularly in the riparian complex. The downed dead large debris exceeded the current volume of standing trees by several fold. Dead aspen biomass was largely a result of flooding of trees by earlier beaver activity. An apparent cycle occurs: aspen stand development, arrival of beaver, felling or drowning of aspen stands from extensive beaver activity, followed by loss of beaver populations and the subsequent redevelopment of aspen stands. Heavy grazing may short-circuit the cycle by removing aspen reproduction.

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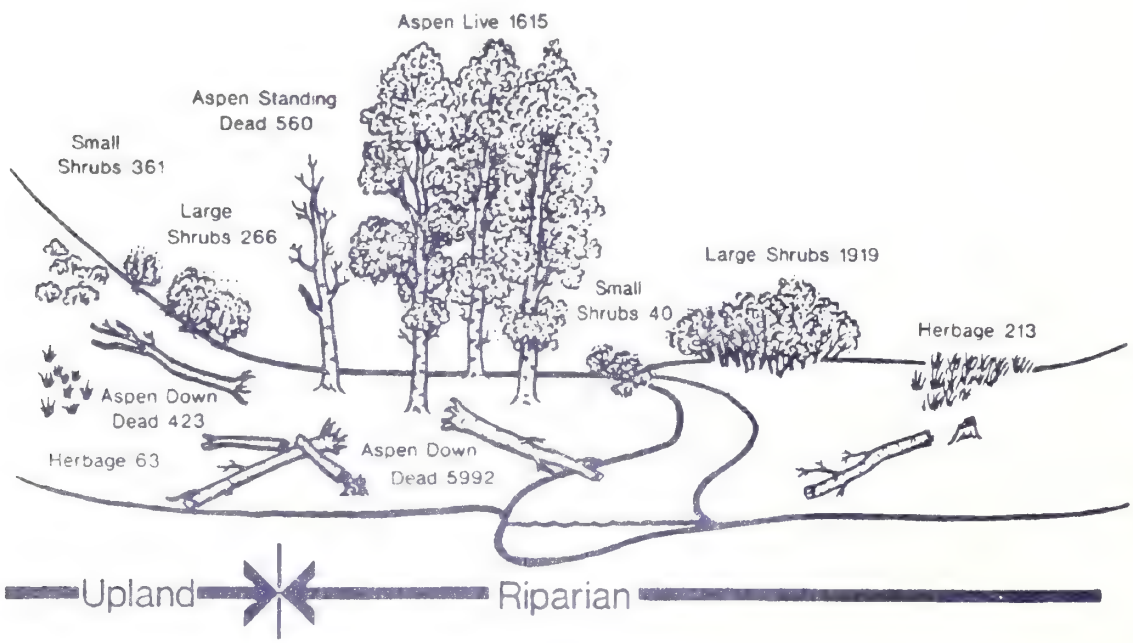

Figure 3—Plant biomass distribution in the fenced area of Deer Creek canyon. Numbers represent grams per square meter ovendry biomass.

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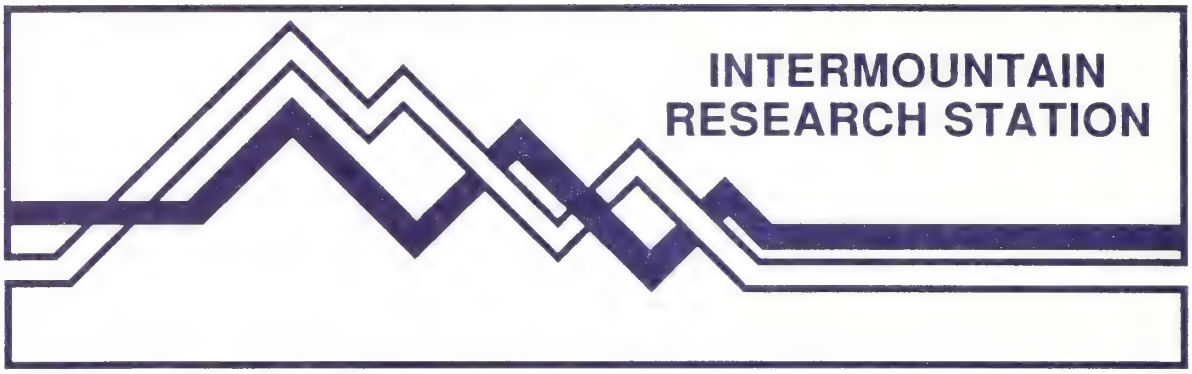
Plant biomass and structure on an area seasonally grazed by cattle was compared to that on a comparable adjoining area fenced for 11 years. In the riparian area less graminoid biomass and height, but more nonwillow large shrub biomass and more soil compaction were the most obvious effects of moderate to heavy cattle grazing. On a nearby area very heavy cattle grazing had a major impact on aspen regeneration and stand structure.

KEYWORDS: *Populus*, *Salix*, *Poa*, soil compressive strength, riparian complex



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How Wilderness Visitors Choose Entry Points and Campsites

Robert C. Lucas

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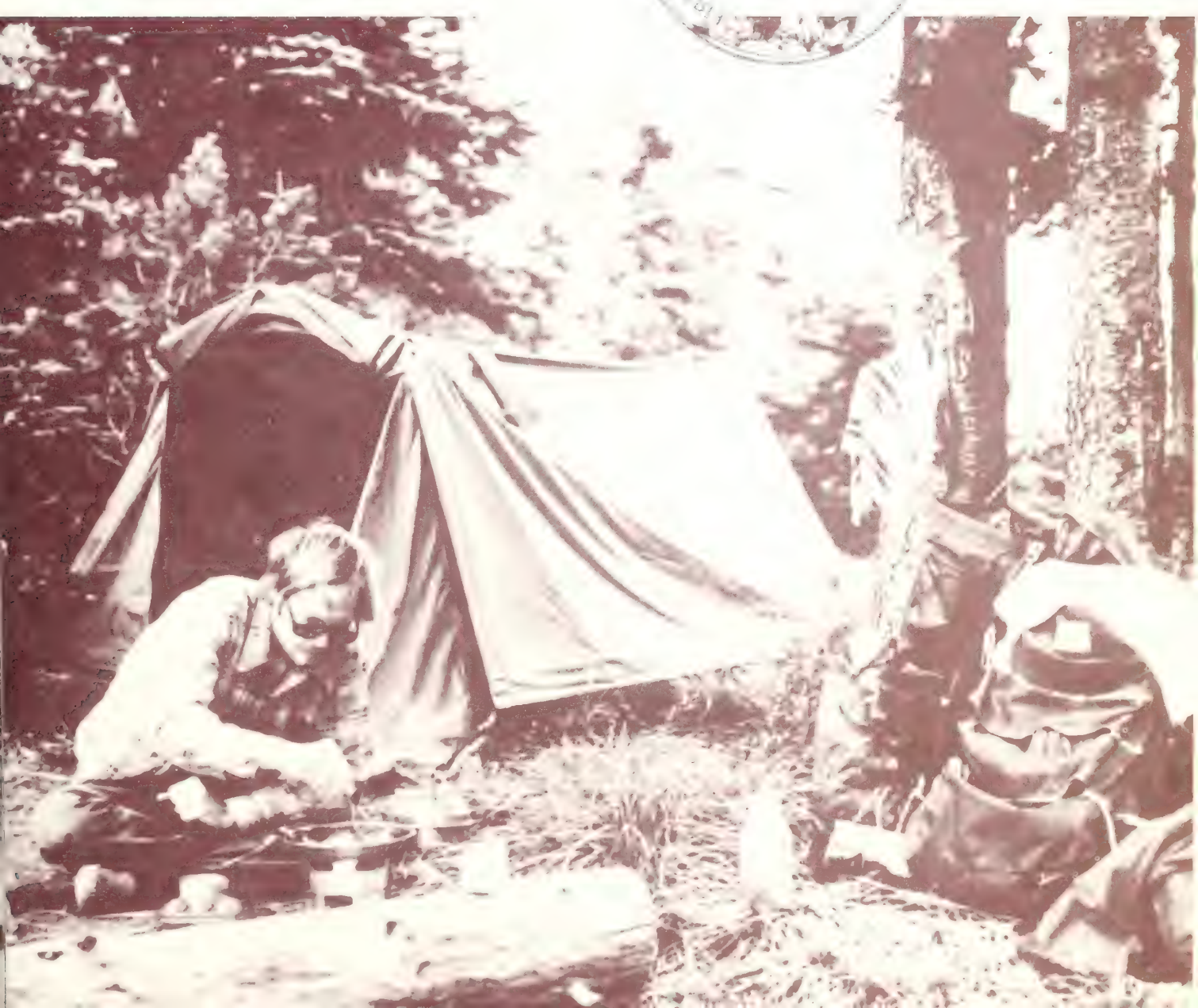

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ROBERT C. LUCAS was principal research social scientist and Project Leader of the Intermountain Station's Wilderness Management research work unit at the Forestry Sciences Laboratory, Missoula, when this study was done, and is now retired. He joined Intermountain Station in 1967. Dr. Lucas received his B.S., M.A., and Ph.D. degrees from the University of Minnesota in 1957, 1959, and 1962. He also studied at the Free University of West Berlin, Germany, and at the University of Chicago. He has authored numerous publications dealing with wilderness management.

RESEARCH SUMMARY

The location choices made by wilderness visitors affect both impacts and solitude, and managers often seek to modify the resulting use distributions. Such attempts have had mixed success. To increase understanding of location choices, visitors who camped in the Bob Marshall Wilderness complex in Montana were studied, focusing on their general decision process, the role of site attributes, and how these varied with visitor characteristics.

Most visitors were looking for new places to visit, hikers more than horse users, but those looking for new places did not put more effort into location choices. Experienced wilderness visitors who were new to the Bob Marshall spent the most time and effort deciding locations. Few visitors contacted the Forest Service for information to aid in their choices, regardless of trip length. Planning usually began a few weeks or more before trips, earlier for longer trips. Maps were the main source of new information. Many site attributes attract visitors, but good hunting and fishing top the list. Many visitors consider alternative trailheads and campsites before they make a final choice. The location of campsites affects choices more than their condition, but hikers and horse users respond to campsite conditions differently. Persons who place a high value on wilderness and solitude put only a little more effort into choosing locations. Campers who want campsites out of sight and sound of other campers reject campsites because they lack seclusion more often than those who prefer less campsite solitude. The longer the trip, the more effort campers make in choosing locations.

Management implications support many current programs and suggest some changes. Managers need to contact more visitors when they are planning trips, especially horse users and hunters. These contacts need to be used to full advantage. Good maps with key information are essential. Minimum-impact education needs to make horse users more aware of resource impacts. Firerings have little affect on campsite acceptability, and efforts to eliminate all of them may be questionable. Information on a variety of site attributes needs to be provided to influence visitors' choices. Camping setbacks from water may conflict with campers' common rejection of campsites "too far from water." Predetermined itineraries, required in some National Parks, make it impossible to examine several campsites before choosing one, which is common behavior. Diverse trail systems best match visitor behavior and preferences.

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How Wilderness Visitors Choose Entry Points and Campsites

Robert C. Lucas

INTRODUCTION

The location choices made by visitors have important implications for wilderness management. The cumulative effect of visitors' choices produces recreational use distributions, and many studies show that these are typically very uneven. A small proportion of access points accounts for most use, and use of trails or water routes is very uneven. Some campsites are heavily used while others are rarely camped on (Hendee and others 1978, chapter 13; Lucas 1980; Roggenbuck and Lucas 1987; Stankey and others 1976). This is important because use distributions strongly affect the two most critical wilderness qualities—natural ecosystems and special visitor experiences.

Recreational use distributions often do not match variation in the ability of areas to support use (Cole 1987). Mismatches between places chosen for camping in wilderness and site durability are thought by many managers to be particularly serious, with fragile sites sometimes receiving use they are poorly suited for.

In addition, campsite location choices can affect the sense of isolation and solitude of wilderness visitors, and seclusion at campsites is the most important aspect of solitude for most visitors (Stankey 1973). Highly uneven use of trailheads contributes to campsite solitude or congestion, and more directly, to numbers and types of encounters between parties and the resulting feelings of solitude. In a broader sense, location choices by visitors, both good and bad choices, strongly influence the quality of their experiences (McCool and others 1985).

As a result of the impacts of visitor distributions on resources and visitor experiences, wilderness managers often want to modify the location of recreational use. This is a common objective of both education programs and recreation regulations.

Education and information have been used to try to shift visitors' entry point selections with varying success (Canon and others 1979; Krumpe and Brown 1982; Lime and Lucas 1977; Lucas 1981). Education and information have also been used in one wilderness in North Carolina to influence visitors' choices of camping areas, with some success (Roggenbuck and Berrier 1981). Other attempts have been made to provide general guidelines to help visitors choose campsites that will reduce their impacts (Cole and Benedict 1983; and various "minimum-impact" education materials), but it is not known how much this has been tried or with what success.

Regulations are also commonly used both to control the amount of use at trailheads and areas they serve through use rationing and to prohibit camping in certain types of places, most often within an established distance of lakes and sometimes streams and trails as well (Washburne and Cole 1983). Specific areas also are closed to all camping in some areas—Glacier and Cold Lakes in the Mission Mountains Wilderness in Montana and all lake basins in the Pecos Wilderness in New Mexico, for example. Some areas, particularly a number of National Parks, require visitors to choose each campsite they will use each night before they begin their trip and then stick to this fixed itinerary—a policy that is unpopular with National Forest wilderness visitors (Lucas 1985a), but how National Park visitors view fixed itineraries is not known.

Most of these attempts to alter wilderness recreational use patterns suffer from a lack of knowledge of the behavior they seek to influence or control. This is reflected in the poor success of many management efforts to redistribute visitor use. Results of education/information programs have varied from success—tripling the number of visitors choosing lightly used trails in Yellowstone National Park (Krumpe and Brown 1982)—to little or no effect (Canon and others 1979; Schomaker 1975). Regulations also vary widely in effectiveness and often fall short of expectations. For example, about half of the campers in the Eagle Cap Wilderness in Oregon were reported to be violating prohibitions on camping close to lakes (Lucas 1983). Most campers in Glacier National Park, which requires fixed itineraries, are said by managers to be in the wrong campsite after 5 or 6 days.

Managers probably could more effectively influence or modify use distributions if they had better answers to questions such as: How do visitors make location choices? who makes decisions? when do they decide? what factors do they consider? and which are most important to them? Managers could better decide between education and regulation if they understood what sort of location-decision process they were dealing with. Managers using educational techniques could better tailor messages and their delivery to visitors with an improved understanding of how different types of visitors go about choosing places to visit and camp.

PAST RESEARCH

Wilderness location choice processes have been little studied. Two general approaches to studying recreational location choices have been used. Some are based mainly on interviews with campers, asking them what they looked for in a campsite. Other studies analyze the attributes of the sites visitors choose to infer the site qualities that characterize desirable recreational use locations.

Frissell and Duncan (1965) reported that nearly half of the respondents in the Boundary Waters Canoe Area Wilderness said they looked at more than one site before making their final choice. The most common reason for

rejecting a site was that it was too small for the party's tent or tents. When questioned about an ideal campsite, island location was mentioned by 45 percent, flat tent spots by 39 percent, firewood availability by 30 percent, good landing area for canoes or boats by 27 percent, and protection from wind by 24 percent. Functional characteristics were far more influential than esthetics or impact levels. Frissell and Duncan concluded that, beyond a preference for islands, "choice of a campsite seems to be controlled largely by what is conveniently available when it is time to stop for the day." They also estimated that 63 percent of campsites were on islands, and 91 percent were in pine forest types.

Hutchinson and Lime (1972) also studied campsite choices in the Boundary Waters Canoe Area Wilderness. They collected data by means of trip diaries given to visitors at the beginning of trips. Visitors usually chose among a few sites in the general vicinity. Boat campers camped earlier and were influenced more by closeness to fishing spots. Islands and peninsulas were popular.

Clark and Stankey (1986) classified site attributes in Southeast Alaska as requisites, facilitators/attractors, and constrainers/detractors. The Alaska Public Survey indicated "favorite sites" for dispersed recreation had the following attributes: remoteness; beaches, boat access, and moorage; salt water fishing; good beachcombing, hiking, and walking opportunities; wildlife and birds; undisturbed natural areas; places to get away from others; and scenery. Esthetic and natural qualities are prominent on this list, along with functional attributes. Based partly on this and on other information, five requisite attributes were selected (landslope, tidal area, bathoslope, shoals, and wind exposure) to identify potential recreation sites from air photos and maps. Field checking has indicated good success in identifying usable sites, but they may or may not have been used by recreationists so far. Only about 20 percent of the shoreline in a case study area was classified as usable.

In Wyoming, Heberlein and Dunwiddie (1979) reported use of campsites at one popular wilderness lake over a 33-day period varied from 0 to 14 nights, based on observations. The authors were unable to relate campsite attributes to selection by campers, except to a subjective "attractiveness rating." Experienced campers selected sites isolated from other campers, however. Here, only esthetic factors emerged—not functional attributes.

Zuckert (1980) found that popular campsites near Charlotte Lake in Kings Canyon National Park, CA, tended to be close to entry points, close to trails, highly visible, and worn. Visitors spent little time searching for campsites or seeking secluded sites. Experienced campers selected somewhat different sites than inexperienced visitors. Perceptions of overuse and crowding explained little about choices.

Brunson (1989) compared the importance ratings of campsite attributes by three types of visitors to a portion of the Alpine Lakes Wilderness in Washington. Responses to questions about primary activity were used to classify visitors as campers, hikers, or climbers. Campers rated solitude attributes highest, followed by functional attributes. Hikers reversed that order. Climbers were most concerned with attributes that facilitated climbing, such as view of the mountain to be climbed and proximity to climbing routes.

Several studies have examined attitudes about acceptable wilderness campsite conditions (Martin 1987; Shelby and Harris 1986). These studies have not included campsite selection, but they have implications for choice and satisfaction.

Mackay (1987) analyzed the role of recreation specialization on desires for information about recreation sites and preferences for site characteristics for Montana hikers and anglers. Information desired did not vary; site preferences did. Mackay also reviews a wide variety of choice models. Williams and Huffman (1986) related specialization to trail selection as it relates to use redistribution. Similar to Mackay (1987), they found difference in site preferences but not in information use.

Other studies have examined other types of recreation location choices and other kinds of human activity. They are not closely related to wilderness trail and camp choices and will not be reviewed here.

OBJECTIVES

This study has three major objectives:

1. Determine the major characteristics of visitor choices of trailheads and campsites (including such factors as decision lead time, sources of information, extent of consideration of alternatives, and preferences for variety/novelty vs. familiarity).
2. Explore site attributes that are important to visitors in choosing some trailheads and campsites and rejecting others.
3. Determine how choices and attribute importance are related to major visitor characteristics (such as experience, method of travel, local vs. out-of-state residence, and hunting vs. nonhunting).

METHODS

The data were collected as part of a repeat survey of visitors to the Bob Marshall Wilderness complex in 1982. The Bob Marshall Wilderness complex (BMWC), located in northwestern Montana, consists of three contiguous National Forest wildernesses—the Bob Marshall, the Great Bear, and the Scapegoat (fig. 1). The three areas straddle the Continental Divide and total more than 1.5 million acres. Four National Forests and five Ranger Districts administer portions of the total area.

Other data from this study were analyzed to identify trends, from 1970 to 1982, in use patterns, user characteristics, attitudes, and preferences, and were published (Lucas 1985b). The 1982 survey also included a section on trailhead and campsite choice—18 questions in all. These had no 1970 counterparts and thus were not part of the trend analysis. Other data collected on visitors and their activities provide information that enables analysis of the association of choice behavior and visitor characteristics.

The details on sampling procedures are in Lucas (1985b). The general approach was a mail questionnaire to a sample of people contacted in the field at about 50 trailheads, in person at most entry points and with special registration stations at lightly used trailheads.

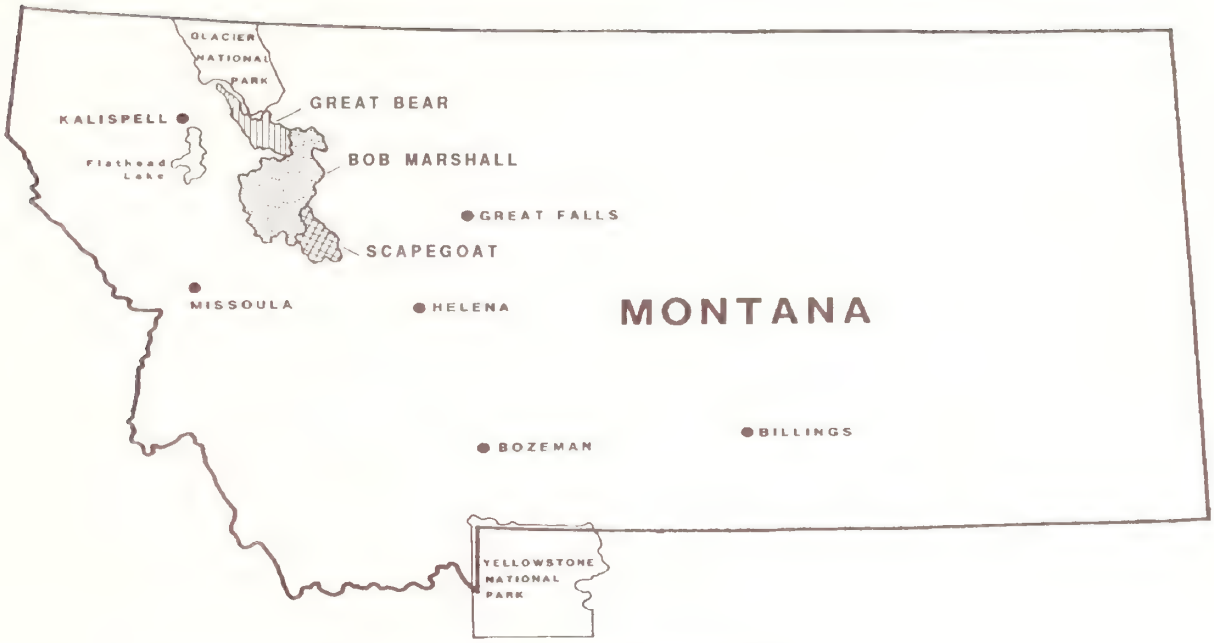

Figure 1—Location of the Bob Marshall, Great Bear, and Scapegoat Wildernesses.

Both summer and fall visitors were sampled. Adult (16 or older) individuals were sampled, rather than groups or group leaders. Day-users and campers were both included, but only campers' location choices will be analyzed in this paper because day-users visit so little of the large wilderness, were not involved in campsite choices, and have less potential impact.

The total sample consisted of 785 questionnaires completed and returned. The rate of return was 82 percent. Minor trailheads were oversampled, and questionnaires were weighted less than 1 to equalize all responses. The weighted sample totaled 531. The weighted total for campers was 413. The three areas will be analyzed as one unit.

Data are presented for hikers, horse users (including horseback riders and a few hikers using packstock—only about 4 percent of all horse users), and rafters. Rafters usually either flew into the Shafer airstrip in the Great Bear Wilderness to start float trips down the Middle Fork of the Flathead River or went in on horses to float the South Fork of the Flathead River in the Bob Marshall Wilderness. The rafter sample is small—18 or fewer respondents in most tabulations—so data reported separately for them should be treated cautiously. Sample size for hikers is 209 and for horse users 186. Totals vary among tabulations because of the varying focus of questions (for example, only campers involved in choosing campsites are analyzed in some tables) and a few incomplete questionnaires.

THEORETICAL PERSPECTIVE

There are a number of theoretical concepts relevant to recreation choice behavior, many of which are described and evaluated in Stankey and McCool (1985). Some theoretical models assume perfect knowledge of settings and their attributes and complex balancing of positive and negative attributes. Some assume that decisions are determined by environmental conditions and people respond passively. Other models assume partial knowledge and more limited rationality (Watson and others in press). Cognitive development models are commonly used in this approach; these models focus on the information an individual has and how the information is used to make choices. Visitors are viewed as actively perceiving and internally shaping the environment around them to make choices (Watson and others in press). Increasing cognitive development leads to increasingly complex, discriminating preferences and information processing (McCool and others 1985).

This cognitive development framework suggests that, in general, the investment of effort in gathering information and making location choices increases as involvement with wilderness and commitment to it increase. The underlying theory is described in more detail in Lucas (1981) and is portrayed schematically in figure 2.

This general theoretical framework guides the following analyses, but formal hypotheses are not tested. The location choice process is complex, poorly understood, and this study can only suggest some of the important aspects of visitor choices of trails and campsites.

RESULTS AND DISCUSSION

The general location choice process will be described first. Factors related to choices will then be discussed. Then the data on the role of various site attributes and differences among different types of visitors will be described. Implications for management will be discussed in a subsequent section.

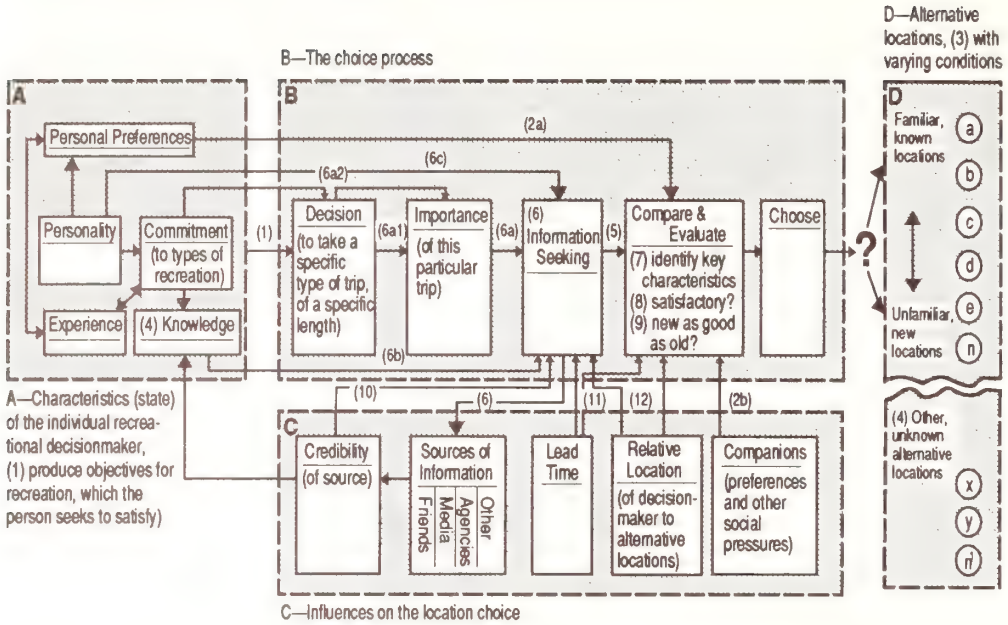

Figure 2—The relationship among the components of recreational location choice behavior. (Numbered components and relationships correspond to description of the theory in Lucas 1981.)

The General Location Choice Process

In choosing places to visit, some visitors prefer to visit new areas each time, while others enjoy going back to old familiar places. Most people do some of both (table 1), but more people prefer novelty than familiarity. The differences among visitors with different methods of travel are statistically significant; specifically, visitors traveling with horses are more often familiarity seekers than hikers.

Most wilderness campers do not contact the Forest Service for information before their visit (table 2). Less than one-fourth seek information; hikers are most likely to contact the Forest Service, horse users least likely, in part because many employ outfitters and rely on them for needed information. The differences are statistically significant.

The most common way of contacting the Forest Service is to visit an agency office (65 percent of those who contacted the Forest Service). More than one-fourth telephoned, and one-eighth wrote, with some contacting the Forest Service in more than one way. Differences in types of contacts among visitors traveling various ways are not large.

Trailhead Choices—Most of the sampled visitors (59 percent) chose or helped choose a trailhead. Hikers were more often involved than horseback riders (65 percent compared to 52 percent), mainly because outfitters often selected trailheads for horse users. Rafters were also less likely to choose a trailhead (56 percent), again because of a major role for outfitters. The differences among travel methods are statistically significant.

Trailhead choices were usually made at least a week before the trip (table 3), and 39 percent were made a month or more before the trip. Visitors using horses plan farther ahead than hikers. Rafters plan even farther ahead. This probably reflects both the greater role of outfitters in horse and raft travel and the more involved preparations necessary for horse travel or river floating. Differences are statistically significant.

Visitors learn about trailheads in many ways, but studying maps is the most common, reported by close to half of all visitors (table 4). Information from friends and personal knowledge from previous trips are also common, while all other sources are rarely used. Forest Service employees ("rangers") are cited by only 5 percent of visitors, and very rarely by anyone except backpackers. There are other substantial and statistically significant differences among visitors traveling various ways (table 4). Hikers study maps the most and use written sources most, horse users rely largely on previous experience, and rafters depend mainly on information from friends.

Reasons for choosing trails were varied, and most people listed more than one (table 5). The most common reason was access to opportunities for good fishing and hunting (37 percent). A wide range of "other" answers were next most common, particularly for hikers. Most were one-of-a-kind responses, often site specific, but the attraction of loop trails and the problem of snow on high country trails were each mentioned several times. Hikers differed substantially from horse users for three reasons. Hikers more often cited "a new area" and "less crowded," and less often mentioned "close to home." The small sample of rafters gave very different reasons, frequently citing only fishing and hunting, familiarity, and "less crowded." Differences among travel methods are statistically significant.

About one-third of the respondents reported considering other, alternate trailheads in addition to the one they

Table 1—Preferences for novelty or familiarity; percentage of total for each method of travel (omitting first-time wilderness visitors)[1]

Prefer to visit:	Method of travel			Total
	Hikers	Horse users	Rafters	
New areas	31	15	27	24
Revisit same areas	11	20	9	15
Both of above	58	65	64	61

[1] $n = 314$ (weighted); $\chi^2 = 12.3261$; $p = 0.02$.

Table 2—Percentage of total campers contacting the Forest Service for information about the wilderness before their trip; percentage of total for each method of travel[1]

Did you contact Forest Service?	Method of travel			Total
	Hikers	Horse users	Rafters	
No	67	85	76	76
Yes	33	15	24	24

[1] $n = 400$ (weighted); $\chi^2 = 14.6791$; $p = 0.001$.

finally chose to visit. Hikers considered alternates slightly more than horse users (nonsignificant), and rafters much less (only 9 percent).

Reasons for rejecting alternate trailheads were numerous and diverse (table 6). None stood out sharply, but the most common, all ranging from 10 to 13 percent of the total, were "too far from trailhead to destination in the wilderness," "too crowded," "too long a drive to reach the trailhead," "trail too difficult or steep," and "time constraints." There were no statistically significant differences among different travel methods.

Campsite Choices—More than half of all campers choose the first campsite they find in the general vicinity of where they intend to stay either most or all of the time (table 7). At the other extreme, about one-fifth say they always consider more than one campsite before choosing. Looking at it in another way, table 7 implies that 79 percent of the campers rejected a campsite at some time on their visit to the Bob Marshall Wilderness complex. Differences among travel methods were small.

When specifically asked, 25 percent of the campers reported rejecting a campsite because of its condition (table 8) and 37 percent because of its location (table 9). Backpackers rejected campsites most often because of both condition and location, and rafters least often. In both cases, the differences among travel methods were statistically significant.

The most common conditions that caused campers to reject sites differed sharply among visitors with different travel methods (table 10). Hikers said horse manure, too much bare ground, and litter were the conditions they found unacceptable enough to pass up a site. Scarce grazing for stock was the only reason reported often by horse users who rejected a site, and the main reason given by hikers—horse manure—was almost unmentioned. The other common hiker reasons, bare ground and litter, were cited far less often by horse users. Only four rafters rejected sites because of condition, but too much bare ground was the most common reason.

In contrast, problems with location of campsites leading to rejection (table 11) differed little among hikers and horse users. The main reasons were: location too close to a trail, too far from water, and too close to other campsites. The first and third reasons suggest solitude seeking; the second is a functional attribute. Only two sampled rafters rejected campsites due to location, in both cases because other campsites were too close.

Table 3—Timing of trailhead choices by campers in the Bob Marshall Wilderness complex; percentage of total for each method of travel[1]

Lead time	Method of travel			Total
	Hikers	Horse users	Rafters	
Less than 24 hours	16	4	0	11
24 hours to 1 week	25	23	0	24
1 week to 1 month	24	29	9	26
More than 1 month	35	44	91	39

[1] $n = 258$ (weighted); $\chi^2 = 22.6511$; $p = 0.001$.

Table 4—Sources of information about trailheads reported by campers involved in choice; percentage of total respondents for each method of travel[1]

Source of information	Method of travel			Total answers
	Hikers	Horse users	Rafters	
Studied a map	52	36	18	44
Told by friends	32	36	73	35
Been there before	23	47	18	33
Forest Service employees	7	2	0	5
Guidebooks	7	3	9	5
Magazines	8	1	0	4
Newspapers	1	1	0	1
Signs	2	0	0	1
Other	11	11	18	11
Don't remember	2	0	0	1

[1] $n = 255$; $\chi^2 = 41.0362$; $p = 0.005$.

Table 5—Reasons for choosing the trailhead used; percentage of total camper respondents who were involved in trailhead choice for each method of travel[1]

Reasons	Method of travel			Total answers
	Hikers	Horse users	Rafters	
Access to good fishing or hunting area	36	38	73	37
Been there before, familiarity	23	26	73	24
Close to home	17	30	9	23
Easy trail	20	22	9	21
A new area, variety	22	17	10	19
Less crowded	21	14	55	19
Other reasons	36	27	27	31

[1] $n = 240$ (weighted); $\chi^2 = 31.9271$; $p = 0.001$.

Table 6—Reasons for rejecting other trailheads, percentage of total campers who rejected a campsite; percentage of total for each method of travel[1]

Reasons	Method of travel			Total answers
	Hikers	Horse users	Rafters	
Too far to destination from trailhead	12	16	0	13
Too crowded	14	6	0	11
Too long a drive to trailhead	8	16	8	12
Trail too difficult or steep	8	16	0	11
Time constraints	12	6	0	10
Road too poor	8	0	0	5
Wanted to visit new area	6	3	0	5
Lack of fishing or hunting	2	3	0	2
Problems for horses	0	3	0	1
Private property, access closed	0	3	0	1
Other	25	39	12	29

[1] $n = 83$; $\chi^2 = 19.6700$; $p = 0.80$ (NS).

Table 7—Answers to "Did you take the first available campsite you found in the general area where you intended to stay?"; percentage of total respondents who were involved in the choice for each method of travel[1]

Answer	Method of travel			Total
	Hikers	Horse users	Rafters	
Always	21	19	33	21
Usually	28	37	33	32
Sometimes	30	26	14	27
Never	21	18	20	20

[1] $n = 347$; $\chi^2 = 5.2739$; $p = 0.50$ (NS).

Table 8—Proportion of campers who rejected an available campsite because of its condition; percentage of total for each method of travel[1]

Rejected a campsite	Method of travel			Total
	Hikers	Horse users	Rafters	
No	68	82	92	75
Yes	32	18	8	25

[1] $n = 361$; $\chi^2 = 10.8627$; $p = 0.005$.

Table 9—Proportion of campers who rejected an available campsite because of its location; percentage of total for each method of travel[1]

Rejected a campsite	Method of travel			Total
	Hikers	Horse users	Rafters	
No	57	69	86	63
Yes	43	31	14	37

[1] $n = 360$; $\chi^2 = 8.6011$; $p = 0.05$.

Table 10—Campsite conditions that caused rejection of campsites; percentage of total rejecting a campsite because of condition for each method of travel[1]

Conditions causing rejection	Method of travel			Total
	Hikers	Horse users	Rafters	
Horse manure	55	1	33	39
Bare ground, erosion	42	20	67	38
Litter	40	28	33	38
Grazing for horses scarce	2	79	0	24
Campfire remains	20	16	33	18
Firewood scarce	18	21	33	18
Damaged trees	15	4	33	12
Other	26	10	33	21

[1] $n = 97$; $\chi^2 = 73.9205$; $p = 0.001$.

About half of all campers report at least sometimes "purposely leaving the trail to look for a campsite," especially hikers (58 percent). About two-thirds of the respondents generally select established, previously used campsites (table 12). Only 16 percent generally camped on new, previously unused sites, while 19 percent used both types of campsites. Hikers and horse users were similar, but rafters were very different, usually camping on new sites, and the difference was statistically significant.

Factors Related to Location Choices

Importance of Wilderness—Visitors who report that wilderness is more important to them would be expected to invest more time and effort in the decision process (longer lead times, more consideration of alternatives, more off-trail campsite searching, more seeking information from the Forest Service), but this was true only to a limited extent.

Most visitors (78 percent) reported that wilderness was "extremely important" to them, the strongest answer available. Another 18 percent answered "very important," leaving only 4 percent for weaker responses. This limited variation hampers analysis of the effects of the importance of wilderness.

The visitors who assign higher importance tend to be a little more involved in location choices and to plan slightly farther in advance, but the differences are not statistically significant. Similarly, there are weak, statistically nonsignificant tendencies for persons for whom wilderness is most important more often to consider other trailheads and campsites, and to reject campsites because of location but not condition. Searching off the trail for campsites is more common by persons reporting the highest levels of wilderness importance, but the relationship is not statistically significant. Camping on previously unused campsites also is more common by those for whom wilderness is most important (statistically significant), which implies more effort to locate potential campsites.

Persons who value wilderness highly were slightly more likely to contact the Forest Service (and to use guidebooks), but the relationship is not statistically significant.

Table 11—Campsite location characteristics that caused rejection of campsites; percentage of total rejecting a campsite because of location for each method of travel[1]

Location characteristics causing rejection	Method of travel			Total
	Hikers	Horse users	Rafters	
Too close to trail	55	38	50	49
Water too far away	42	56	50	47
Too close to occupied camp	30	39	75	34
Poor view	20	18	25	20
Other	23	16	25	22

[1] $n = 144$; $\chi^2 = 7.0998$; $p = 0.50$.

Importance of Solitude—Visitors who place a high value on solitude would be expected to invest more in choices, and especially, to consider alternative places more than do other visitors, but, again, the relationship is weak.

Visitors were asked, "What were your main reasons for choosing this kind of area (a roadless wilderness) instead of some other kind of recreation area?"—indicating the importance they attached to each of 10 possible reasons, one of which was "to experience solitude." About 61 percent answered solitude was "very important," 25 percent "somewhat important," and 13 percent "not important." These responses were used to classify visitors in terms of the importance of solitude.

Visitors who placed a high importance on solitude were significantly more likely to be involved in choosing trailheads than those who considered solitude less important, and slightly less likely to have an outfitter make the choice. Planning lead times, contrary to expectations, were significantly *shorter* for high-solitude visitors. This appears to be partly because outfitter guests have long planning lead times but low solitude importance (although outfitter guests report high general wilderness importance).

High-solitude-importance visitors more often considered alternative trailheads and campsites, but neither relationship is statistically significant. Solitude seekers also rejected campsites a little more for both condition and location reasons, but not significantly so. They were more likely to report that a location was rejected because it was too close to other campsites or to a trail, although this difference fell just short of statistical significance. Solitude seekers also searched off trail for campsites and contacted the Forest Service for information more often, but again numbers fell short of statistical significance

It appears that those who say solitude is very important to them do not do much more than other visitors to try to find solitude.

Campsite Solitude—Visitors who prefer no one else camped near them seem likely to reject campsites because of location close to other campsites or trails more often than do those who prefer some other campers nearby, and study results confirm this relationship.

Most campers (84 percent) preferred no one else camped within sight or sound of their campsite. The two measures, importance of solitude and standards for campsite solitude, are similar, but are only moderately correlated, with significant chi-square values, but the value of gamma is only 0.35. (Gamma is a measure of correlation for ordinal data, and is interpreted like a conventional Pearson correlation coefficient.) As expected, campers preferring full solitude did reject campsites because of location more often than those who preferred some other campers present. They did so significantly more often because of occupied camps nearby (almost four times as often), and more often because a trail was too close, 52 percent compared to 32 percent (nonsignificant at 0.05).

The visitors who wanted isolated camps also were significantly more likely to search off trail for a place to camp, and to choose a trailhead because it led to less crowded areas. They also had significantly longer planning lead times.

The expected relationship is generally supported by the data.

Trip Length—Longer trips would be expected to involve more investment in choices than do shorter trips; and, in fact, they do.

Visitors taking longer trips had statistically significantly longer planning lead times. Most trips of a week or more were planned at least a month in advance, while only one-fourth of trips of 3 nights or less were planned a month ahead. People on longer trips were more likely than people on short trips to choose trailheads and areas reached by them because they were less crowded and less likely to choose because a trail was close or easy. There was no association between trip length and consideration of alternative trailheads.

People on longer trips were significantly more likely to contact the Forest Service for information about the wilderness. More than one-third of people on trips of a week or more contacted the agency, but only 22 percent of those on shorter trips did. Only 7 percent of 1-night campers contacted the Forest Service. People on longer trips were more likely to write, while those on short trips called on the telephone more often.

People on long trips significantly more often rejected campsites because of condition, but not because of location. Visitors on long trips reported they slightly less often took the first available campsite (not statistically significantly so). There was a nonsignificant tendency for people on longer trips to search more off trail for campsites. People on long trips were significantly more likely to camp on previously unused sites, which usually requires extra effort to locate suitable places.

Novelty vs. Familiarity—Novelty seekers (those who prefer to visit new areas) would seem likely to invest more in the choice process than do familiarity seekers (those who prefer to continue visiting the same areas), but this is not what was found. Furthermore, it would seem probable that hunters are more often familiarity seekers than are other visitors, and horse travelers are more often familiarity seekers than are hikers, and these two more specific relationships turned out to be true.

Novelty seekers were expected to have longer planning lead times than people who usually visit places they have been to before, but the opposite was true, and statistically significant. Novelty seekers do use maps more than twice as often as other visitors, and, perhaps obviously, were far

more likely to choose a trail because it led to a new area. They consider alternative trailheads more, but not significantly so. They contact the Forest Service significantly more often. Familiarity seekers reject campsites due to both condition and location less than novelty seekers (many visitors said they did some of both—seeking new areas and revisiting areas). Novelty seekers were more likely to reject a campsite because it was too close to another occupied campsite and much more likely to do so because it was too close to a trail. They were not more likely to search off trail for a campsite, nor much more likely to camp on previously unused sites.

There is little support for the general relationship. Perhaps the novelty seekers are more spontaneous and do less detailed planning than expected.

The expectation that hunters are more often familiarity seekers stems from the assumption that their motivation for visiting wilderness is more narrowly focused on wildlife abundance and less on scenery or other qualities where variety would seem more important. The data show this; 24 percent of hunters say they prefer to revisit the same areas, compared to only 13 percent of nonhunters, and 20 percent prefer new areas, while 25 percent of nonhunters do. (Most of both types say they do some of both.) But the relationship does not quite reach significance at the 0.05 probability level.

The belief that horse travelers are more often familiarity seekers is based on the idea that areas suitable for horse travel and grazing are limited and exploration of new areas more difficult, favoring sticking with trips that have worked well before. As expected, visitors traveling with horses are significantly more likely to be familiarity seekers than are hikers.

Previous Experience—One would expect experienced wilderness visitors who are newcomers to the Bob Marshall Wilderness complex to invest more in the choice process than either beginners or veterans of the Bob Marshall, and generally this proved to be true.

Visitors were classified into three experience groups: (1) those who had visited other wildernesses before, but not the Bob Marshall Wilderness complex ("experienced newcomers"), (2) those on their very first wilderness trip ("beginners"), and (3) those who had visited the Bob Marshall complex before ("veterans"). Veterans were the largest group, 47 percent of all visitors, followed by experienced newcomers, 32 percent, and beginners, 22 percent.

Experienced newcomers are expected to make more effort to select locations because they have some general wilderness experience so they know what types of information are relevant and have developed views about site acceptability, both of which many beginners may lack. Veterans often are visiting areas they are already familiar with, and all have some general experience with the Bob Marshall complex so they need less information and also may have formed more realistic standards for acceptable sites, settling more readily for what is usually available.

How far ahead visitors chose entry points does not agree with the expectation. Experienced newcomers had significantly shorter lead times, veterans longer, and beginners intermediate. The variable role of outfitters is probably part of the reason for this pattern. Beginners used outfitters the most, and experienced newcomers the least, significantly so. Arrangements with an outfitter normally are made well in advance of a trip.

Experienced newcomers were far more likely to study maps to select entry points—63 percent doing so compared to only 33 percent of veterans. They also were twice as likely to consider alternate trailheads as were other experience categories. They contacted the Forest Service a little more than beginners (32 percent compared to 28 percent), significantly more than veterans (18 percent). They also wrote Forest Service offices the most, and most often contacted the agency in two or three different ways (visit, telephone, write).

Experienced newcomers were significantly more likely to reject a campsite because of condition (37 percent), compared to only 13 percent of beginners. They also were significantly more likely to reject a campsite because of location (47 percent), compared to beginners (only 24 percent). They were significantly more likely to search off trail for campsites, and beginners least likely. Veterans were intermediate in all of these instances. There were no differences among experience types in frequency of use of existing or previously unused campsites.

Except for planning lead time, the observed relationships largely support the expectations about the role of previous experience.

Lead Time—The longer the decision lead time, the more likely it seems that visitors would seek information from the Forest Service, but there is no significant difference in contact with the agency associated with planning lead time. In fact, those who decide "on the way" are most likely to contact the agency. Perhaps they are forced to do so because many have not taken the time to study maps or contact friends for information.

Method of Travel and Use of New or Established Campsites—Backpackers are expected to be more likely to choose campsites not previously camped on than are horse travelers, but it does not appear that they do.

The expectation is that backpackers are able to use smaller, more varied sites that are not well suited to holding or grazing horses, and that most of the sites suitable for horse users already have been found and used over the years. There also may be differences in attitudes and preferences about desired campsite conditions and isolation that lead more backpackers to choose previously unused sites.

The data do not support the expectation (table 12). There are statistically significant differences among travel method categories, but they stem mainly from the rafters, who usually camped on new sites.

Experience and Personal Involvement in Choices—Persons who choose or help choose the trailhead their group uses are expected to be more experienced (experienced both generally and in the BMWC) than those who are not involved in choices, and this is what was found.

This expectation is common sense, and follows logically from the general theoretical perspective on recreational site choices described earlier. The data strongly support the expected relationship. Persons who had visited any

Table 12—Proportion of campers reporting use of new sites, not camped on before, or already established sites, previously camped on; percentage of total for each method of travel[1]

Generally used campsites that:	Method of travel			
	Hikers	Horse users	Rafters	Total
Had not been camped on before	15	14	53	16
Had been camped on before	67	65	33	65
Both types of campsites	18	21	14	19

[1] $n = 363$; $\chi^2 = 16.6302$; $p = 0.005$.

wilderness before were much more likely to be involved in choice of trailheads than beginners (88 percent compared to 65 percent). Those involved in location choices were also significantly more likely to have visited the Bob Marshall Wilderness complex before, 67 percent compared to 46 percent for those not choosing. The more previous visits, the more likely visitors were to participate in location choices. This relationship was significant (chi-square probability less than 0.005, and gamma 0.50). Those choosing had much more site-specific experience also, giving "been there before" as a reason for choosing an entry point significantly more often than other visitors. People involved in choices also began visiting wilderness at younger ages than those not helping choose.

Other Factors Related to Choices

Several other visitor characteristics might be related to location choices. Residence in Montana or out of State is one that has not been examined, and hunters have been compared to nonhunters only briefly, so far.

Residence—Visitors from outside Montana have significantly less experience in wilderness in general, and the Bob Marshall complex in particular, compared to residents of the State. Significantly more out-of-staters travel with outfitters and, related to this, fewer personally choose trailheads or campsites. Out-of-state visitors tend to be novelty seekers significantly more than residents. Their lead time on location choices goes to extremes compared to Montanans'—either very short or very long. They use maps, guidebooks, and "rangers" significantly more, and contact the Forest Service more, significantly more often writing to the agency. They choose trailheads mainly because of good hunting and fishing and because of less crowding. Nonresidents were only slightly more likely than Montanans to reject a campsite because of condition, but far more likely to do so because of horse manure. They were no more likely to pass up a campsite because of location, and their reasons were not much different than residents. They also were no more likely to search off trail for a campsite.

Hunting Participation—Hunters differ from nonhunters in how they deal with location choices in many ways. The differences are similar to those between hikers and horse users described earlier. This is not surprising because almost all hunters in the Bob Marshall Wilderness complex use horses, but the differences tend to be greater for hunters, suggesting that summer horse users are somewhat different from hunting season horse users.

Hunters have significantly more Bob Marshall experience than nonhunters, but about the same amount of general wilderness experience. Hunters less often choose trailheads, and outfitters choose for them significantly more than for nonhunters. They have longer decision lead times. They use all information sources less, using almost none except "been there before," maps, and friends. They choose trails mainly (61 percent) for hunting opportunities, and, compared to nonhunters, far less often cite "less crowded" or "new area." Hunters consider alternate trailheads about as much as nonhunters, but reject trails because of difficulty much more.

Hunters tend to contact the Forest Service less (nonsignificantly), and, if they contact the agency at all, usually do so in person, significantly less often writing or telephoning than nonhunters. They consider alternative campsites significantly less, and reject campsites due to condition less, and only because of scarce grazing (table 13). Hunters also were significantly less likely to pass up a campsite for location shortcomings, and almost never for reasons related to isolation and solitude. They were significantly less likely to search off trail for a campsite than were nonhunters, but were more likely to camp on previously unused places (25 percent compared to 15 percent).

Summary—Most visitors are looking for new places to visit, at least on some trips. Few contact the Forest Service. Most visitors are involved in location choices—not just party leaders. Planning usually begins a few weeks or more before the trip, particularly for longer trips. Maps are the main source of new information. Many features attract visitors to the places they choose, but good hunting and fishing head the list. Many visitors weigh several alternative entry points and campsites before they make a final choice. Campsite location shortcomings result in more rejection than problems with conditon, but hikers and horse users differ sharply in how they respond to various campsite conditions.

Table 13—Campsite conditions that caused rejection of campsites; percentage of total hunters and nonhunters rejecting a campsite because of condition[1]

Conditions causing rejection	Hunter	Nonhunter	Total
Horse manure	0	45	39
Bare ground, erosion	18	41	38
Litter	28	39	38
Grazing for horses scarce	64	18	24
Campfire remains	0	21	18
Firewood scarce	19	18	18
Damaged trees	0	13	12
Other	9	22	21

[1] $n = 97$; $\chi^2 = 22.0476$; $p = 0.005$.

The process of choosing locations is complex and variable. The theoretical perspective used here assumes visitors have only partial knowledge and process information in ways that usually are not rigorous nor always strictly rational. Thus, it is probably not surprising that some expectations were supported by the data and some were not. People who placed a high importance on wilderness and on solitude as a wilderness characteristic tend to put a little more effort into choosing locations, but the relationships are not strong. Visitors who want a campsite out of sight and sound of other campers do reject campsites that do not offer seclusion significantly more than those who prefer some camping neighbors. The longer the trip, the more effort campers make in choosing locations.

People who prefer to visit new areas do not put more effort into choosing locations. Horse users and hunters are more inclined to revisit old familiar places than are backpackers. Experience plays a significant role in how people make location choices, with people who are experienced wilderness visitors but new to the particular area putting the most effort into choices. Contact with the Forest Service is rare regardless of how far ahead people plan trips. Choice of new or previously used campsites differs little among hikers and horse users. The more experience visitors have, the more they participate in choosing wilderness locations.

Overall, the theoretical structure suggested here seems to account for much but not all of the results. There clearly is lots of room for improving the theory and collecting data that better measure important decisions by visitors.

MANAGEMENT IMPLICATIONS

What implications can be drawn from these results that would aid managers in influencing visitor behavior in ways to reduce impacts and improve the quality of visitors' experiences?

Research on visitor location choices implies a few new management actions and provides additional support for many actions recommended earlier, based on other types of studies, and already employed by many managers. Most of the implications relate mainly to information and education programs—some in general, some particularly for minimum-impact (or "no trace") use, and others mainly for efforts to redistribute visitor use. Several implications relate to management of trails and campsites.

Implications for Information/ Education Programs

A low proportion—only about one-fourth—of all visitors contact the managing agency for information about the area to make location and other decisions, and the contact rate is even lower for horse users and hunters. Most contacts are made by visiting a Forest Service District Ranger Station or other office. This implies the need to treat every public contact as very valuable, and too rare to squander. Contacts have the potential to affect many future trips, especially for persons who usually revisit the same parts of a wilderness, and information may spread through networks of friends and thus indirectly reach some of the large majority who do not contact managers.

The low contact rate also implies a need to provide incentives for more people to contact the agency voluntarily, especially horse users and hunters who combine particularly low contact rates with high potential for causing impacts. Many contacts are in person. Knowledgeable agency people are needed who display the "Good Host" attitude and are dedicated to raising "customer satisfaction" as promoted by the Forest Service's current National Recreation Strategy. Good written materials are also essential, especially for written contacts. If contacts are really useful, as well as pleasant, the word will get out, and more visitors will decide it is worth their time to check with the agency. Stationing an employee at well-used trailheads could be effective and worthwhile.

Visitors making longer trips more often contacted the Forest Service for information. This is clearly good, because the longer trips are more significant and have more potential for impact.

Maps are the most used source of information. This means the agency needs to have good maps available, with all key information on them, and use maps as a major information and education tool.

Many wilderness trips are planned well in advance. This reemphasizes how important it is to reach visitors at home, during the planning process. This is especially true for efforts to redistribute use (Lime and Lucas 1977; Lucas 1981), but also for minimum-impact messages, particularly for practices that require specific equipment, such as stoves to reduce campfire impacts, water bags or collapsible jugs to make camping farther from water feasible, or high-line ropes for tethering horses away from trees. Video tapes, either loaned or given away, may offer a powerful new technology for reaching visitors at home. Most families now have VCR's; tapes are inexpensive; well-done programs could hold attention better than written materials; and people can view them at times convenient to them, perhaps several times. Research to test the effectiveness of video tapes would be valuable.

The people who make location decisions tend to be the more experienced visitors. This has both good and bad implications for information and education. Good: decision-makers have general familiarity with wilderness travel and camping so messages do not all necessarily have to start from scratch. Bad: information and education often need to overcome previous ideas, some of which may be erroneous.

Solitude, especially campsite solitude, seems important to many visitors, as reflected in reported choices of trails and campsites. This adds some support to conclusions based on responses to questions about solitude in the abstract.

People who feel wilderness, solitude, and campsites isolated from other campers are most important all put more effort into location decisions. This probably makes them the easiest to reach with information *and* education and to influence. This may provide an opportunity to aid them in finding the degree of solitude they seek. But others who are more difficult to reach and influence may have higher potential for adverse impacts.

Implications for Minimum-Impact Education

Horse users and hunters have different, less-demanding ideas about acceptable wilderness campsite conditions. They pass up campsites less often, and primarily for reasons related to functional, utilitarian aspects, not minimum impact. They appear to be relatively insensitive to many types of impacts stressed in current minimum-impact messages, impacts which bother other types of visitors. This poses a challenge to managers to motivate horse users and hunters more effectively to change or reduce their behaviors that cause bare ground, damaged trees, and horse manure accumulations in campsites.

Horse manure in camps is the leading reason why backpackers reject campsites, but horse users seem to accept it or ignore it. Minimum-impact education should stress ways of holding horses outside camps, scattering "meadow muffins," and also could inform backpackers where to look for campsites not used by parties with horses.

Firerings do not seem to be a serious problem in the view of most visitors, and seldom affect location choices. Perhaps minimum-impact education should encourage leaving one small, clean firering rather than eliminating all traces, which often results in repeated rebuilding of fires in different places, spreading impacts (Cole 1989). This might be a good compromise that seems to be consistent with visitor behavior and values.

Tree damage also is not widely perceived as a serious problem, and affects few campsite choices, especially by horse users and hunters. Tree damage, far more than firerings, has serious, long-lasting, cumulative effects. The challenge is to raise visitor awareness of tree damage as a problem and of the importance of reducing it.

Implications for Redistributing Recreational Use

Many visitors seek new places much of the time, and these variety seekers contact the Forest Service more than other visitors. If managers want to encourage some visitors to shift their use to specific places, many visitors should be receptive, because they are already looking for variety. This is most true of backpackers; there is a bigger challenge in redistributing horse users and hunters.

Many location choices for horse users and hunters are made for them by outfitters. If major redistribution of horse and hunter use is desired, managers will need to work with outfitters to achieve appropriate use distributions.

Fishing and hunting are powerful attractions, and they influence many location decisions, along with many other location characteristics. If information is meant to redistribute much use, it must cover a variety of location characteristics, and excluding information on hunting and fishing opportunities seriously weakens the effectiveness of such efforts.

Off-trail searching for campsites and considering alternative campsites are moderately common behavior, but if managers think encouraging campers to choose campsites that are more isolated or durable is desirable, they need to encourage more such behavior.

A common reason for rejecting campsites is "too far from water." This implies a possible conflict with programs requiring camping a specific distance from shorelines. There is a need to reexamine the reasons and necessity for such regulations, and if they are deemed essential, to explain them well to motivate compliance by visitors.

Rigid, preselected campsite itineraries also do not seem to match the actual behavior of many wilderness campers. They fairly often look over and reject campsites on the ground, something that is impossible with advance choice in a Ranger Station. This supports other research reporting low popularity of these inflexible systems (Lucas 1985a).

Implications for Management of Trails and Campsites

Visitors' reasons for choosing and rejecting trails clearly show a diverse market. There is demand for easy as well as more challenging trails, both easily accessible and more remote trailheads, and for loop trails and also destination trails. The concepts underlying the Recreational Opportunity Spectrum (ROS) and Limits of Acceptable Change (LAC) seem vindicated.

Campsite-solitude seekers often reject campsites because of other nearby occupied campsites. This has implications for information programs to aid such people in finding more isolated places to camp, but it also implies another benefit from programs to eliminate some closely spaced campsites, often surplus for even maximum use (Cole 1982), and rehabilitating such sites.

Wilderness visitors choose trails and campsites in complex and variable ways. As a result, few simple, "cookbook" recommendations are possible, but the descriptions and analyses of the location choice process in this paper should help wilderness managers strengthen their programs.

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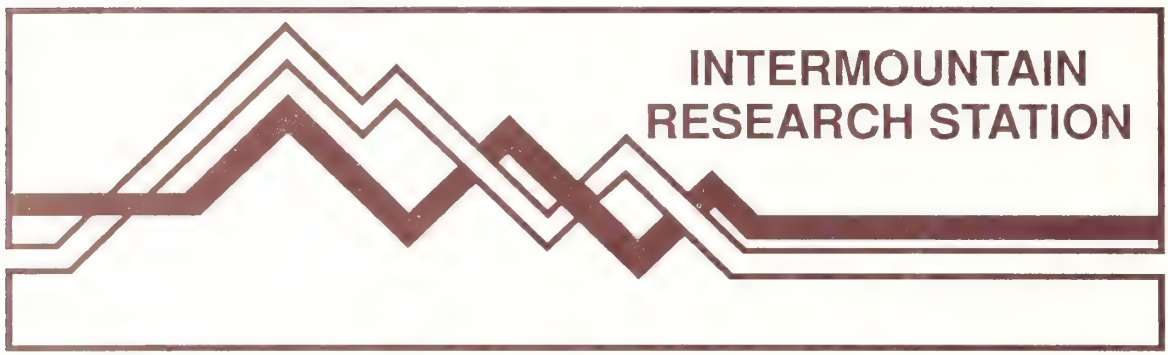
The process of selecting trailheads and campsites is described for visitors to the Bob Marshall Wilderness complex in Montana. Factors influencing decisions by different types of visitors are analyzed. Implications, particularly for information and education programs, are presented.

KEYWORDS: choice behavior, location choices, trailheads, Bob Marshall Wilderness



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Predicting Equilibrium Moisture Content of Some Foliar Forest Litter in the Northern Rocky Mountains

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RESEARCH SUMMARY

Forest foliar litters that make up the fine fuels involved in spreading wildfires may vary in equilibrium moisture content, EMC, by 7 percent or more. This research reports the differences in EMC by species, the changes in EMC due to relative humidity and fuel temperature, and the predictions of EMC by applying a form of the Gibbs free energy equation. Results show that EMC's of only a few litter types are similar to the EMC of wood and that all litter types exhibited lower EMC's than wood at high temperatures and humidities. Test conditions ranged from 278 °K (40 °F) to 322 °K (120 °F) and from 10 to 90 percent RH.

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INTRODUCTION

The past half century has seen many attempts to quantify moisture content, MC, of wildland fuels and to incorporate these values into systems for predicting fuel flammability and potential fire behavior. Hardy (1983) describes the work of Harry T. Gisborne, who was studying fuels in the 1920's, and who eventually devised a fire danger meter that depended on the moisture content of wood dowels (Gisborne 1948).

Several studies have investigated moisture content to determine its influence on wildland fuel flammability: of wood (Simard 1968); of fine fuels such as hardwood leaves (Dunlap 1932); fine fuels in southern forests (Blackmarr 1971), Australian forests (King and Linton 1963), and forests of eastern Canada (Van Wagner 1972); and fine fuels entered into the early United States National Fire Danger Rating System, NFDRS (Keetch 1966). Air temperatures, near 23 °C (80 °F) and relative humidity from 20 to 90 percent have often been used to study fuel moisture content and flammability.

Study results generally indicated that moisture content of wood varies among tree species (Simard 1968) and that the moisture content of wood is usually lower than that of nonwoody fuels such as grass, needles, and leaves (Anderson and others 1978; Van Wagner 1972). Nevertheless, the current NFDRS (Cohen and Deeming 1985) is based on the moisture content of wood sticks, drawn from the Wood Handbook (USDA FS 1974). Adsorption and desorption are represented by a single curve over the entire range of humidity and fuel-surface temperatures. Moisture values drawn from such curves would typically under predict EMC for nonwoody fuels and would overpredict their flammability and potential fire behavior. The research reported here was initiated to determine EMC's of various nonwoody, foliar litter fuels over a range of temperatures and humidities and thus improve the accuracy of flammability and fire behavior predictions.

Determining an EMC for each fuel type that poses a fire potential would be an unreasonable and unnecessary task, particularly if a small set of fuel groups with similar EMC's could be calculated. Nelson's research (1983, 1984) on the sorption of water by cellulosic materials provides that capability. Nelson developed an empirical model, based on the observed exponential relationship between a thermodynamic variable, Gibbs free energy, and the EMC of a cellulosic material. The Gibbs free energy per gram of sorbed water is measured in terms of absolute temperature, degrees Kelvin, and relative humidity, RH. Nelson (1983, 1984) noted that earlier researchers had reported the change in Gibbs free energy as a function of moisture content, MC, for cellulosic materials (Babbitt 1942; Kelsey and Clarke 1956; Stamm and Loughborough 1935). In addition, Anderson and McCarthy (1963) had reported an exponential variation for the differential heat of wetting as a function of moisture content.

While illustrating the possible formation of foliar litter groups in terms of EMC's, the research described here also provides another test of the applicability of Nelson's equation to materials with less cellulose content than wood. Woody materials have cellulose contents near 75 percent, while conifer needles have contents near 40 percent (Susott 1980; Susott and others 1975).

METHODS AND MATERIALS

Field Procedures

Foliar litters consisting of grasses, deciduous leaves, and conifer needles were collected in western Montana and northern Idaho for study. One sampling was done in the fall after the current-year leaf and needle cast, collecting only the recently cast dead foliar litter. Another sampling was done in the late spring collecting just the weathered foliar litter. The general areas of sampling are shown in figure 1, with the following specific collections: western white pine (*Pinus monticola* Dougl.) at the Priest River Experimental Forest in northern Idaho; lodgepole pine (*Pinus contorta* Dougl.) and Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), in the headwater drainages of Fish Creek in Montana; Engelmann spruce (*Picea engelmannii* Parry), subalpine fir (*Abies lasiocarpa* [Hook.] Nutt.), western redcedar (*Thuja plicata* Donn.), and grand fir (*Abies grandis* [Dougl.] Lindl.), in the general area of the Powell Ranger District in Idaho. Litter samples collected in the vicinity of Missoula, MT, were ponderosa pine (*Pinus ponderosa* Laws.), quaking aspen (*Populus tremuloides* Michx.), western larch (*Larix occidentalis* Nutt.), and cheatgrass (*Bromus tectorum* L.). The fuels were brought to the Intermountain Fire Sciences Laboratory in Missoula, MT, where they were mechanically sorted, cleaned without washing, and placed in cool, dry storage until the testing was done.

Figure 1—General locations of sampling for the foliar litter studies.

Laboratory Procedures

Three temperature-controlled cabinets were used to condition litter samples. Two cabinets were used to establish high and low MC starting points, and the third one maintained a constant atmospheric humidity. The high-humidity condition was established over water at the test temperature in the first cabinet and the low-humidity condition of 2 to 3.5 percent relative humidity (RH) was set in the second cabinet, with ambient air heated to 322 °K (120 °F). This procedure was similar to Van Wagner's (1972) and provided comparability. Although the possibility of a decrease in hygroscopicity existed because of influences like internal and external physical stresses, the results indicated that this was not a major influence. Within each cabinet, RH was monitored with the aid of a dew point detector. Samples of a selected litter were weighed, placed in cabinets 1 and 2, weighed periodically until the weight change had stabilized, and then placed in cabinet 3 so the EMC was approached with desorbing and adsorping litter samples. Again, samples were weighed periodically until the weight change had stabilized. This period of time was from 1 to 2 weeks, depending on the foliar litter being tested. When the samples had reached their final values, they were processed with xylene distillation to determine the final MC. Saturated salt solutions were used to maintain the relative humidity at each of the test temperatures used. Table 1 shows the humidities achieved at the various temperatures.

An initial test series was done at 295 °K (71 °F) with litter samples considered to be recently cast. The results indicated the samples were often a mixture of recently cast and weathered materials. A second series was tested at 300 °K (80 °F) using litter samples collected more carefully. Four of these fine fuels, ponderosa pine and Douglas-fir needles, cheatgrass, and quaking aspen leaves, were also tested at 278 °K (40 °F) and 322 °K (120 °F) to investigate the change in EMC with temperature. Fuel and air temperatures were the same in these tests, and two or more replications were done for each sample at each temperature and relative humidity.

Results from these tests were organized by litter type, recently cast or weathered condition, adsorption or desorption, and the temperature-humidity combinations.

Data Analysis

In addition to studying the differences in EMC values for the various foliar litter fuels, a method of estimating EMC at different temperatures and humidities was investigated. The most promising approach was the Gibbs free

Table 1—These saturated salt solutions maintained the relative humidities shown for the test temperatures

Salt	Temp	RH	Temp	RH	Temp	RH	Temp	RH
	°K	Pct	°K	Pct	°K	Pct	°K	Pct
LiCl	278	17	295	13.5	300	11.8	322	12.7
$MgCl_2$	278	—	295	34.0	300	30.0	322	—
$Mg(NO_3)_2$	278	61	295	53.0	300	53.0	322	48.0
NaCl	278	—	295	74.0	300	70.5	322	—
KNO_3	278	82	295	85.0	300	78.0	322	88.0
C	5		22		27		49	
F	41		72		80		120	

energy exponential relationship presented by Nelson (1983). The decrease in Gibbs free energy per gram of sorbed water is described by (Nelson 1983, 1984; Skaar 1972):

$$\Delta G = -(RT/M)\ln(RH/100), \text{ cal/g} \quad (1)$$

where R is the universal gas constant, 1.9872 cal °K/mole; T is the absolute temperature, (°C + 273 = °K); M is the molecular weight of water, 18.0153 g/mole; and RH is the relative humidity in percent. Limits on ΔG were set by considering the values as RH approaches zero and 100 percent. When the RH goes to zero, ΔG would become negatively infinite but is limited to a value that is defined when the RH has reached a small but finite value of 0.66 percent. Therefore ΔG_0 represents the Gibbs free energy change possible at very dry conditions:

$$\Delta G = \Delta G_0 \text{ when MC} = 0. \quad (2)$$

ΔG_0 is determined from a plot of $\ln(\Delta G)$ versus MC and extrapolating to MC = 0.

When the RH approaches 100 percent, the MC approaches fiber saturation moisture content, MC_s, and the Gibbs free energy goes toward zero so:

$$\Delta G = 0 \text{ when MC} = MC_s). \quad (3)$$

Nelson (1983, 1984) found a simpler logarithmic model to have better linearity with $\ln(\Delta G_0) = 0$ (or $\Delta G = 0$) when MC equals MC_s:

$$\ln(\Delta G) = \ln(\Delta G_0)\,(1 - MC/MC_s). \quad (4)$$

To be as accurate as possible, equation 4 was modified by defining MC_v as the moisture content value when $\ln(\Delta G) = 0$ and is only an approximation of fiber saturation moisture content, MC_s under conditions of desorption. For adsorption, MC_v approximates the product of MC_s and the hysteresis ratio (the average ratio of adsorption to desorption moisture contents). Equation 4 then becomes:

$$\ln(\Delta G_0) = \ln(\Delta G_0)\,(1 - (MC/MC_v)) \quad (5)$$

and may be applied to adsorption and desorption EMC data.

This equation can be modified to a form suitable for testing experimental data by least squares regression analysis when $A = \ln\Delta G_0)$ and $B = -(A/MC_v)$:

$$\ln(\Delta G) = A + B(MC). \quad (6)$$

Values for ΔG were determined by equation 1 for each temperature and relative humidity tested. The ΔG values were combined with the observed EMC values to develop the data sets used to determine the coefficients A and B. Six to ten observations of EMC were used in each combination (table 2). Analysis showed that MC was a predictor of $\ln(\Delta G)$ for species, temperature, and RH. Within the range of temperatures tested, I developed a quadratic or linear equation to predict A and B for a given, °K, temperature. The form of the equations for predicting A or B is:

$$A = C_n + C_{n+1}(\text{TEMP}) + C_{n+2}(\text{TEMP}^2) \quad (7)$$

where

TEMP = fuel surface temperature, °K

C_n, C_{n+1}, and C_{n+2} = constants of regression.

With a given temperature and RH, we could then determine $\ln(\Delta G)$, $\ln(\Delta G_0) = A$ and $MC_v = -(A/B)$ and estimate MC using:

$$MC = MC_v\,(1 - (\ln(\Delta G)/\ln(\Delta G_0)). \quad (8)$$

This provided the means to evaluate the variability in EMC of foliar litter fuels, check for similar groups of litter, define how both the sorption process and the state of weathering influence EMC, and show how the EMC's of foliar litter relate to the wood fine fuel EMC used in the NFDRS. The EMC's of the forest foliage litter fuels are presented in the accompanying figures and referenced to the EMC of wood at the same temperature. Curves for wood were generated by regression equations produced in the same way as for foliar litter but using the EMC data in table 3-4 of the Wood Handbook (USDA FS 1974).

RESULTS

All the tests showed a typical sigmoid-shaped curve for EMC as a function of RH when EMC is assumed to approach zero as RH nears zero (fig. 2). Nearly all the foliar litter samples showed higher EMC's than calculated by the method used for wood sticks in the NFDRS. Recently cast Douglas-fir needles showed a sorption change in EMC at 300 °K (80 °F) very similar to that of wood used in the NFDRS (fig. 2). At the same conditions, western larch needles showed the highest EMC's (fig. 2). The other litter samples tested have data located between these two and show that the EMC's can differ by 2 to 6 percent, depending on the litter samples. The weathered samples showed similar responses, but are shifted toward higher EMC's and have less hysteresis among the foliar litter samples (fig. 3). The adsorption and desorption curves in figures 2 and 3 show the hysteresis loop to be 2 percent or less EMC for RH from 10 to 90 percent and a temperature of 300 °K (80 °F).

The EMC's at 278 °K (40 °F) and 300 °K (80 °F) were higher than those of wood, but at 322 °K (120 °F) a significant decrease in EMC occurred (fig. 4). This decrease is more pronounced than reported for wood in the Wood Handbook (USDA FS 1974) and as used in the NFDRS. At 278 °K (40 °F), moisture contents of the foliar litter samples could be 4 percent higher at low RH and as much as 7 percent higher at high RH. As the temperature increases, the EMC decreases until at 322 °K (120 °F) all four litter samples have EMC's lower than wood at RH's above 40 percent. Cheatgrass had a small change in EMC, 4.2 to 10.6 percent, as RH went from 12.7 to 88 percent at 322 °K (120 °F) (fig. 4). Ponderosa pine needles' EMC predicted values from equations 6, 7, and 8 show the decrease in EMC at 10, 30, and 70 percent RH as the temperature increases (fig. 5).

Table 2—Coefficents for the regression equation of Gibbs free energy equation, $\ln(\Delta G) = \ln(\Delta G_o)\,(1-(MC/MC_v) = A+B(MC)$ where $A = \ln(\Delta G_o)$ and $B = -\ln(\Delta G_o)/MC_v$. AD = adsorption and DE = desorption

Species	Condition	Sorp	Intercept A	Slope B	Max. EMC MC_v	R^2	No.	MSE
			278 °K					
Cheatgrass, CG	Recent	AD	4.7661	−15.42	0.3091	0.9972	8	0.0552
		DE	5.3671	−16.82	.3191	.9599	8	.2087
	Weathered	AD	4.9450	−16.72	.2957	.9879	8	.1146
		DE	5.4090	−17.69	.3058	.9672	8	.1889
Douglas-fir, DF	Recent	AD	4.4922	−17.71	.2536	.9856	8	.1250
		DE	5.2952	−14.36	.3688	.8995	8	.3304
	Weathered	AD	4.8490	−17.02	.2849	.9992	8	.0290
		DE	5.5010	−17.99	.3059	.9872	8	.1177
Ponderosa pine, PP	Recent	AD	4.7654	−17.05	.2796	.9968	8	.0586
		DE	5.7350	−20.57	.2789	.9791	8	.1508
	Weathered	AD	4.8478	−16.47	.2944	.9954	8	.0709
		DE	5.5151	−18.20	.3030	.9835	8	.1339
Quaking aspen, QA	Recent	AD	4.5277	−12.32	.3676	.9594	8	.2101
		DE	5.3474	−14.80	.3612	.9788	8	.1517
	Weathered	AD	4.7716	−12.82	.3722	.9906	8	.1010
		DE	5.6836	−17.01	.3341	.9995	8	.0238
			295 °K					
Cheatgrass, CG	Recent	AD	4.9145	−18.15	0.2566	0.9290	8	0.3068
		DE	5.1989	−18.49	.2812	.9604	10	.2291
Douglas-fir, DF	Recent	AD	4.7141	−17.08	.2760	.9784	10	.1465
		DE	4.7377	−13.99	.3386	.9594	10	.2007
Engelmann spruce, ES	Recent	AD	4.5901	−16.69	.2751	.9643	10	.1881
		DE	4.3865	−10.68	.4108	.9393	10	.2453
Grand fir, GF	Recent	AD	4.7842	−15.84	.3020	.9830	10	.1362
		DE	4.4185	−11.05	.3998	.8933	10	.3418
Lodgepole pine, LP	Recent	AD	4.7646	−18.26	.2610	.9910	10	.1094
		DE	5.1764	−18.10	.2859	.9886	10	.1231
Ninebark, NB	Recent	AD	4.7501	−13.53	.3498	.9176	10	.3028
		DE	5.0120	−15.05	.3330	.9046	10	.3258
Ponderosa pine, PP	Recent	AD	5.0017	−20.09	.2489	.9905	10	.1122
		DE	5.1240	−17.84	.2873	.9849	10	.1417
Quaking aspen, QA	Recent	AD	5.2308	−18.78	.2785	.9901	10	.0989
		DE	5.0881	−15.12	.3365	.9444	10	.2349
Subalpine fir, SF	Recent	AD	4.9898	−21.48	.2324	.9960	10	.0732
		DE	4.8060	−15.93	.3016	.9708	10	.1968
Western white pine, WP	Recent	AD	5.1260	−17.34	.2957	.9879	10	.1152
		DE	5.1667	−13.95	.3703	.9948	10	.0755
Western redcedar, WC	Recent	AD	4.9899	−17.61	.2834	.9894	10	.1086
		DE	4.7710	−13.01	.3667	.9422	10	.2536
			300 °K					
Douglas-fir, DF	Recent	AD	4.6768	−18.92	0.2471	0.9871	10	0.0100
		DE	4.7713	−17.55	.2719	.9650	10	.0271
	Weathered	AD	5.2789	−20.98	.2516	.9823	10	.0137
		DE	5.2840	−18.90	.2795	.9961	10	.0030
Engelmann spruce, ES	Recent	AD	4.4698	−15.44	2896	9647	10	.0274
		DE	4.5928	−15.49	.2964	.9489	10	.0396
	Weathered	AD	4.8936	−17.43	.2808	.9996	10	.0003
		DE	5.1382	−16.74	.3070	.9992	10	.0006
Grand fir, GF	Recent	AD	4.6475	−16.42	.2829	.9837	10	.0126
		DE	4.8952	−18.11	.2703	.9811	10	.0147
	Weathered	AD	5.1336	−16.78	.3060	.9979	10	.0017
		DE	5.4385	−16.74	.3249	.9939	10	.0047
Lodgepole pine, LP	Recent	AD	4.7601	−17.80	.2674	.9908	10	.0071
		DE	5.1552	−18.62	.2768	.9877	10	.0096
	Weathered	AD	5.0319	−17.12	.2939	.9935	10	.0050
		DE	5.3049	−16.84	3150	.9951	10	.0038
Western larch, WL	Recent	AD	4.8922	−14.99	.3264	.9714	10	0222
		DE	5.1903	−15.61	.3326	9658	10	.0265
	Weathered	AD	5.1161	−16.68	.3068	.9926	10	.0057
		DE	5.6226	−18.48	.3043	.9899	10	.0078

(con.)

Table 2 (Con.)

Species	Condition	Sorp	Intercept *A*	Slope *B*	Max. EMC MC_v	R^2	No.	MSE
			300 °K (Con.)					
Ponderosa pine, PP	Recent	AD	4.9588	−18.32	.2706	.9868	10	.0102
		DE	5.3411	−19.71	.2710	.9965	10	.0027
	Weathered	AD	5.1275	−19.46	.2634	.9949	10	.0039
		DE	5.4581	−19.51	.2798	.9954	10	.0036
Quaking aspen, QA	Recent	AD	4.9747	−15.75	.3159	.9783	10	.0168
		DE	5.3707	−17.70	.3035	.9642	10	.0277
	Weathered	AD	5.1099	−15.93	.3209	.9933	10	.0052
		DE	5.3934	−15.49	.3481	.9470	10	.0411
Subalpine fir, SF	Recent	AD	4.6962	−18.25	.2573	.9881	10	.0092
		DE	4.8972	−19.13	.2560	.9732	10	.0208
	Weathered	AD	5.0260	−18.67	.2692	.9947	10	.0041
		DE	5.3391	−19.00	.2810	.9948	10	.0040
Western white pine, WP	Recent	AD	5.0038	−17.44	.2870	.9981	10	.0015
		DE	5.2969	−17.32	.3058	.9934	10	.0051
	Weathered	AD	5.1133	−15.91	.3213	.9981	10	.0015
		DE	5.4419	−16.50	.3298	.9977	10	.0018
Western redcedar, WC	Recent	AD	4.7442	−16.90	.2807	.9838	10	.0126
		DE	4.9530	−17.14	.2890	.9801	10	.0154
	Weathered	AD	5.0398	−15.84	.3181	.9973	10	.0021
		DE	5.2021	−14.44	.3602	.9982	10	.0014
			322 °K					
Cheatgrass, CG	Recent	AD	5.4364	−37.38	0.1454	0.9721	6	0.2348
		DE	6.0096	−42.67	.1408	.9947	6	.1022
	Weathered	AD	5.4710	−42.00	1302	.9338	6	.3617
		DE	6.0549	−52.69	.1149	.9346	6	.3594
Douglas-fir, DF	Recent	AD	4.7339	−23.57	.2008	.9773	6	.2112
		DE	4.8620	−25.77	.1886	.9835	6	.1803
	Weathered	AD	5.6470	−34.95	.1616	9949	6	.0999
		DE	5.9220	−35.74	.1657	.9958	6	.0914
Ponderosa pine, PP	Recent	AD	5.4363	−32.12	.1692	.9959	6	.0904
		DE	5.4314	−30.13	.1803	.9998	6	.0174
	Weathered	AD	5.8920	−36.90	.1597	.9811	6	.1933
		DE	5.9276	−34.52	1717	.9943	6	.1065
Quaking aspen, QA	Recent	AD	6.0343	−39 17	.1540	.9937	6	.1117
		DE	6.4355	−40.90	.1573	.9840	6	.1780
	Weathered	AD	6.2567	−39.48	.1585	9884	6	.1513
		DE	6.7023	−40.37	.1660	.9995	6	.0322

Although the EMC changes converge at low EMC's, the high temperature data have higher intercepts than the other temperatures, and low temperature data tend to have lower intercepts. This is indicated in figure 6, which shows how the $\ln(\Delta G)$ changes with EMC. The species were grouped visually and statistical tests were carried out at the 5 percent significance level to see if the regression lines in a proposed group were parallel and coincident. In a few cases, species could be grouped, but the results were not uniform. No consistent groupings were found for the recent cast or weathered conditions. The reason appears to be that the mean square errors, MSE, are so small that slight variations make significant changes in the computed F values. Instead of grouping by statistical methods, overlays were used to see if grouping by litter types was possible. Inspection indicated the best resolution of the litter types was obtained using ±2 percent EMC bands to group the foliar litter types. At 300 °K (80 °F) and both sorption processes the following groups could be separated in order of increasing EMC:

Recently Cast Litter

Group 1: Cheatgrass
Group 2: Douglas-fir, Engelmann spruce, grand fir, and subalpine fir
Group 3: Ponderosa pine, lodgepole pine, and western redcedar
Group 4: Quaking aspen, western larch, and western white pine

Weathered Litter

Group 1: Cheatgrass
Group 2: Douglas-fir, Engelmann spruce, and subalpine fir
Group 3: Ponderosa pine, grand fir, lodgepole pine, and western redcedar
Group 4: Quaking aspen, western larch, and western white pine

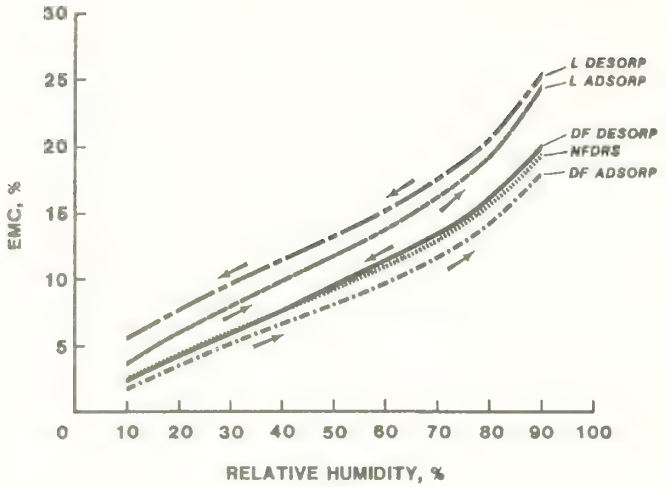

Figure 2—EMC curves of recently cast Douglas-fir needles and larch needles, plotted from Gibbs free energy equations at 300 °K for relative humidity, are compared to EMC values observed for adsorption, desorption, and NFDRS estimates.

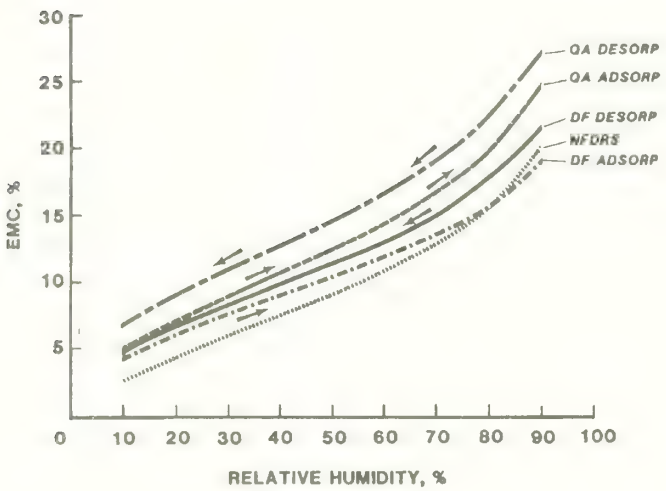

Figure 3—EMC curves of weathered Douglas-fir needles and weathered quaking aspen leaves, plotted from Gibbs free energy equations at 300 °K for relative humidity, are compared to EMC values observed for adsorption, desorption, and NFDRS estimates.

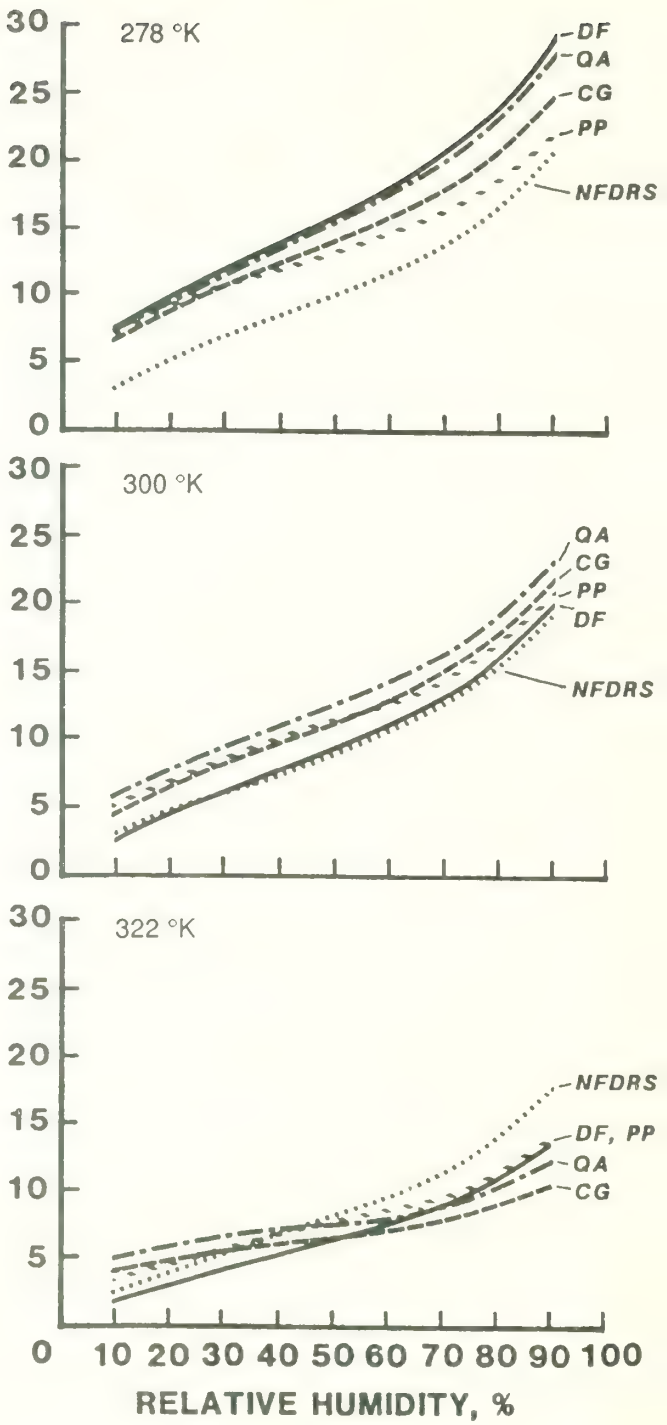

Figure 4—Changes in EMC desorption with temperature and humidity for aspen, cheatgrass, ponderosa pine, and Douglas-fir litter, compared to NFDRS estimates.

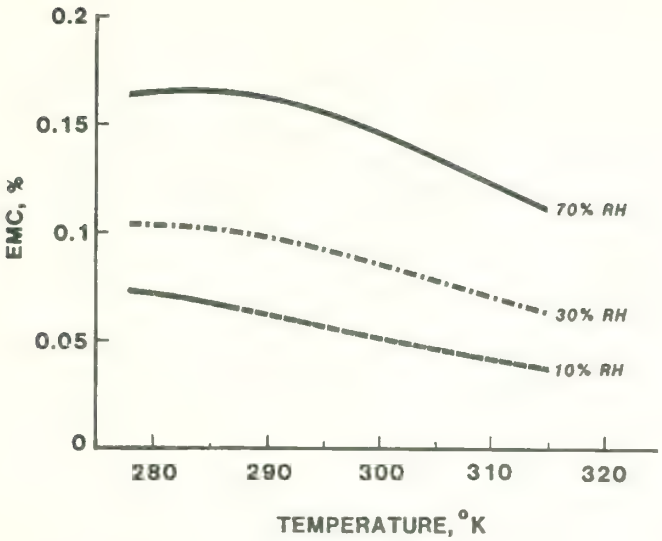

Figure 5—Decreases in recent ponderosa pine needles EMC desorption values at humidities of 10, 30, and 70 percent as surface temperatures increase are predicted and plotted from equations 6, 7, and 8.

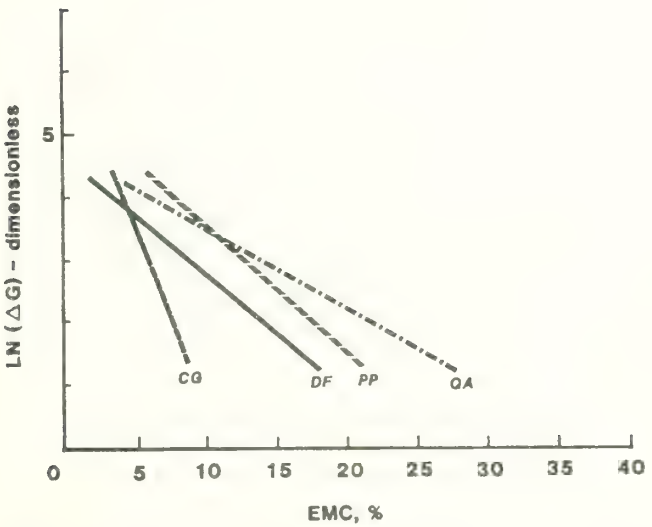

Figure 6—Variations in Gibbs free energy relationship for several litter fuels and conditions: Douglas-fir at 300 °K, recently cast in adsorption; ponderosa pine at 300 °K, recently cast in desorption; quaking aspen at 278 °K, weathered in adsorption; cheatgrass at 322 °K, weathered in desorption.

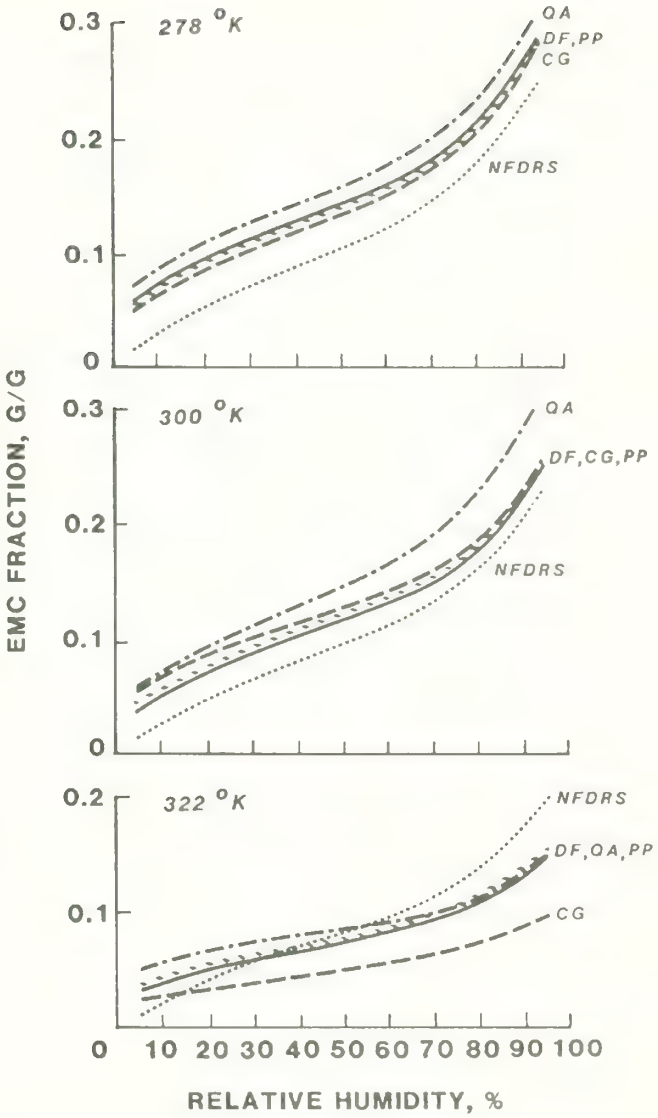

Figure 7—Desorption EMC's of weathered Douglas-fir, ponderosa pine, quaking aspen, and cheatgrass litter compared to wood used in NFDRS estimates. Data from weathered material shows more similarity than data from recently cast material.

Figure 7 illustrates the curves generated from equation 8 and the separation for the litter groups at 278, 300, 322 °K, desorption, and weathered conditions. A general grouping of foliar litter species was seen in the firs and spruce needle EMC data. Pine needle EMC's for recently cast or weathered conditions tended to group.

Coefficients for the Gibbs free energy equation, A and B, were found to be functions of temperature (figs. 4, 7). Data were analyzed at 278, 300, and 322 °K for ponderosa pine needles, quaking aspen leaves, and Douglas-fir needles. For cheatgrass, EMC data taken at 295 °K were used because those at 300 °K were not available. It was found that both A and B could be estimated by quadratic equations where the litter temperature was the independent variable. For cheatgrass, a linear regression provided a better fit for the A coefficient for all conditions except the recently cast material in desorption. This was also true for the Douglas-fir weathered material in adsorption. Each of the litter groups delineated above can be evaluated for expected EMC's by using equation 7 with C_1, C_2, and C_3 values given in table 3 to determine A and C_4, C_5, and C_6 values to determine B and then using equations 6 and 8 to calculate the expected EMC. The coefficients C_1 and C_4, C_2 and C_5, and C_3 and C_6 are given in table 3

Table 3—Coefficients for regression equations to predict A and B as functions of surface temperature for use in the Gibbs free energy equation, $\ln(\Delta G) = A + B(MC_v)$. $A = C_1 + C_2(TEMP) + C_3(TEMP^2)$, $B = C_4 + C_5(TEMP) + C_6(TEMP^2)$, R^2 = coefficient of variation squared, No. = number of observations

	Species			
	Douglas–fir	**Ponderosa pine**	**Quaking aspen**	**Cheatgrass**
		Recently Cast—Adsorption		
C_1	–9.309	26.300	52.639	.414
C_2	.08784	–.15758	–.35223	.01554
C_3	–.0001373	.0002883	.0006445	—
R^2	.98	.98	.99	.94
No.	34	34	34	24
C_4	–295.915	–1,081.460	–1,709.360	–972.061
C_5	1.98014	7.43318	11.90591	6.84375
C_6	–.0035232	–.0129658	–.0208685	–.0122398
R^2	.99	.98	.99	.99
No.	34	34	34	24
		Recently Cast—Desorption		
C_1	64.898	51.842	95.503	81.765
C_2	–.39084	–.30298	–.62584	–.52473
C_3	.0006348	.0004933	.0010847	.0008991
R^2	.99	.99	.97	.93
No	34	34	34	24
C_4	–409.989	–1,000.250	–1,741.360	–1,471.690
C_5	2.87550	6.75430	12.08836	10.26116
C_6	–.0052246	–.0116198	–.0211430	–.0180860
R^2	.99	.99	.99	.99
No	34	34	34	24
		Weathered—Adsorption		
C_1	–.154	43.563	70.514	1.566
C_2	.01809	–.28016	–.46990	.01216
C_3	—	.0005069	.0008397	—
R^2	.90	.97	.99	.99
No	24	24	24	14
C_4	–780.621	–1,234.710	–1,742.930	–1,733.460
C_5	5.47058	8.57029	12.12182	12.00537
C_6	–.0097980	–.0150654	–.0212174	–.0209711
R^2	.99	.99	.99	.99
No	24	24	24	14
		Weathered—Desorption		
C_1	82.609	52.480	141.973	1.219
C_2	–.52508	–.32254	–.93345	.01497
C_3	.0008912	.0005528	.0015943	—
R^2	.96	.91	.98	.88
No.	24	24	24	14
C_4	–1,389.800	–1,193.320	–2,281.030	–2,611.640
C_5	9.54490	8.19501	15.63398	18.08085
C_6	–.0165845	–.0142747	–.0269426	–.0314763
R^2	99	.99	.99	.99
No.	24	24	24	14

and must be carried out to 3, 5, and 7 decimal places, respectively, for the *A* and *B* coefficients to be accurate. Rounding up EMC values imposes a bias so the values are always offset from the observations.

The EMC values over a range of litter temperatures can be estimated from the equations given in tables 2 and 3 developed for the four litter types tested. It appears that these results can be extended to the litter groups by using the equations for the representative litter type because the litter samples could be grouped within ±2 percent of each other. Litter group 1 (recently cast, adsorption and desorption) is represented by the cheatgrass EMC's. Litter group 2 (recently cast, adsorption and desorption) is represented by the Douglas-fir EMC's, while litter group 3 is represented by the ponderosa pine EMC's and litter group 4 by the quaking aspen EMC's. The weathered samples, with adsorption and desorption phases, group in a similar manner but most of the conifers needle types group with the Douglas-fir and ponderosa pine needle data. Groups 2 and 3 could be grouped as one because the calculated EMC's are generally within ±2 percent of each other.

DISCUSSION

The possibility of organizing the various foliar litters into litter groups is encouraging because it suggests that only a few such groups of litters or fuels are needed to describe the general change in EMC. Use of this information does require the user to make observations of the field situation and decide what species are present and whether the foliar litter is weathered or recently cast. Although the EMC data for recently cast litters are useful for a short period of each year, the weathered EMC data will probably be useful throughout the year. Weathering results in the EMC shifting to higher values. The available literature was reviewed for data that could be compared to see if the results are consistent with other measurements. Information published by King and Linton (1963), Blackmarr (1971), and Van Wagner (1972) was used to determine if the EMC's of other fuels could be estimated using regression equations determined in this work. Results were compared to those reported by Nelson (1984) and good agreement was found. In addition, the EMC equations to calculate wood moisture in the NFDRS were checked.

Litter group 1, cheatgrass (recently cast, adsorption and desorption), matched Blackmarr's EMC's for wiregrass (*Aristida stricta* Michx.) and broomsedge (*Bromus secalinus* L.), staying within 2 percent at all the tested RH's. Van Wagner's (1972) EMC data for a grass (*Calamagrostis* sp.) was consistently 2 percent higher. The tussock grass (*Poa caespitosa*) EMC's reported by King and Linton were lower than that for cheatgrass by more than 2 percent and had a different rate of change to RH. The desorption EMC's curve for cheatgrass were 1.5 to 2.0 percent higher than the EMC curve presented for wood.

Litter group 2, fir and spruce needles (recently cast, or weathered, adsorption and desorption), appeared to be unique in that no other needles for these or similar species have been tested. This group's EMC values were found to fit best the eucalypts (*E. obliqu* L'Herit. and *E. radiata* Sieb. ex DC.) leaf data of King and Linton (1963). The EMC's of the eucalpyts stayed within 2 percent of litter group 2 EMC's to an RH of 70 percent, where the eucalyptus litter exhibited higher EMC's. These litters may group because of the extractives, crude fats, or cutin they contain. At 300 °K the litter group 2 EMC's for recently cast, desorption conditions matched the EMC's for wood.

Litter group 3, pines and cedar (recently cast, adsorption and desorption), EMC's behaved similiarly at low RH's with red pine (*P. resinosa* Ait.) from Van Wagner (1972) and radiata pine (*P. radiata*) from King and Linton (1963). At 82 percent RH, however, radiata pine had a 9 percent higher EMC during adsorption. Although none of the litter samples used for comparisons were identified as weathered, five pine species were found to match best with litter group 3 (weathered, adsorption and desorption): eastern white pine, (*P. strobus* L.) and jack pine (*P. banksiana* Lamb.) from Van Wagner (1972); loblolly pine (*P. taeda* L.), slash pine (*P. elliottii* Engelm.), and longleaf pine (*P. palustris* Mill.) from Blackmarr (1971). For this litter group, the match in EMC was always within 2 percent until the RH increased to 80 percent or more. Most of the weathered litter samples corresponding to the litter samples of the recently cast litter groups 2 and 3 merge into the weathered phase of litter group 2.

Litter group 4, quaking aspen, western larch, and western white pine (recently cast, adsorption and desorption), compared well with sugar maple (*Acer saccharum* Marsh.) and trembling aspen (*Populus tremuloides* Michx.) from Van Wagner (1972) up to a RH of 78 percent, where the latter went to higher EMC's. Generally, the EMC's were within 1 percent at RH's below 78 percent. The deciduous leaves used by Blackmarr, southern red oak (*Quercus falcata* Michx.), post oak (*Q. stellata* Wangenh.), and mockernut hickory (*Carya tomentosa* Nutt.), compared best with the litter group 4 (weathered, adsorption and desorption) EMC's. The adsorption values at midrange RH for the oaks were about 2 percent lower in EMC than those found in this study.

The use of EMC's for the litter groups discussed here, rather than those for wood, to represent foliar litter would produce some significant changes in estimating fire danger or fire behavior. For instance, all of the litter groups' EMC's are within 1 percent of each other at 278 °K (40 °F) and 10 percent RH, but are 3.5 to 4.5 percent higher than those for wood. At 300 °K (80 °F) and RH's from 10 to 90 percent, pine needles are about 2 percent higher in EMC than wood and fir needles. Deciduous leaves are about 3.5 percent higher than wood over the same RH range. This means that for a system based on the EMC of wood, the fire danger or fire behavior in needle and leaf fuels can be overestimated. But the reverse can happen at higher temperatures, such as the 322-°K (120-°F) test temperature, where all of the EMC's for foliar litters become less than that for wood above 40 percent RH, with cheatgrass being lower by nearly 7 percent. In these cases, the litter may be ignitable sooner than expected or continue to burn even though the RH shows an increase.

SUMMARY

EMC values for some foliar litter, fine forest fuels, such as Douglas-fir needles, were close to that of the NFDRS values for wood for different temperatures and humidities. EMC's of most litter samples, however, are higher than those of wood. For recently cast, adsorption and desorption, these litters can be classified from lowest to highest EMC's into four general groups: grasses, spruce and fir needles, pine and cedar needles, and aspen and larch foliage. At 300 °K (80 °F) the spruce, fir, and ponderosa pine needles had the lowest EMC's even after having weathered over winter for 6 months. The rest of the weathered litter groups are, in order from lowest to highest EMC's, the pines; the grasses, and then larch, aspen, and cedar.

The EMC's can be estimated by equations that relate the change in moisture content to temperature and humidity. This approach uses the relationships given in the Gibbs free energy equations. The estimates are within ±2 percent MC of the observed values for temperatures of 278 to 322 °K and RH's of 10 to 90 percent. Litter EMC's deviate from the EMC for wood enough that separate calculations for fire danger rating or fire behavior estimates may be required. These equations provide a means for estimating EMC and MC that allows resolution of the differences that exist in fuel types.

Temperature had a significant effect on EMC. Foliar litters' EMC's were much lower at high temperatures than wood. This may explain the increased flammability of some fuels on hot days or when heated by direct sunlight so the fuel temperature is higher than the air temperature.

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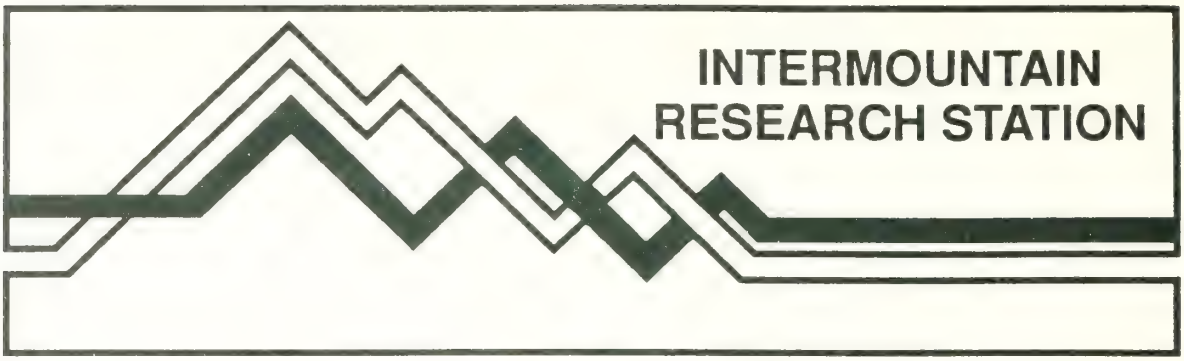
Forest foliage that comprises much of the forest floor litter has higher equilibrium moisture content, EMC, than woody components. The EMC's at 300 °K were found to increase as follows: grasses < fir-spruce needles < pine-cedar needles < aspen leaves-larch needles. Equations that express Gibbs free energy associated with moisture content were used to develop regression equations that predict the EMC's from temperature and relative humidity, RH, for temperatures between 278 °K (40 °F) and 322 °K (120 °F) and RH's between 10 and 90 percent.

KEYWORDS: fuel moisture, fire behavior, flammability, fuels, wildland fire



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Sage Grouse Status and Recovery Plan for Strawberry Valley, Utah

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DEC 0 5 1990

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RESEARCH SUMMARY

This report describes the decline of sage grouse (*Centrocercus urophasianus*) in the Strawberry Valley of Utah, probable causes of the decline, results of a 4-year sage grouse radio tracking study, current population levels, and a sage grouse recovery plan.

Sage grouse numbers were estimated between 3,000 and 4,000 birds in 1939. Bird numbers were estimated between 250 and 350 in 1983. Current 1989 estimates placed bird numbers at 160 to 185 birds. This is a decline of 94 to 96 percent over the 1939 estimates.

The decline of sage grouse in the Strawberry Valley of Utah was due to a number of factors (converting shrublands to grasslands, increased human activities [camping, roads, summer homes], enlargement of the reservoir, rodent control through the use of poisoned grains). During the late 1950's and until the mid-1970's the valley was sprayed with herbicides to convert the big sagebrush lands to grasslands. Sage grouse have a near-obligate relationship with big sagebrush and its close relatives. These spraying projects destroyed thousands of acres of sage grouse habitat. Other factors have also added to the decline. Habitat has been lost due to flooding of the Stinking Springs strutting ground complex, construction of summer homes on Windy Ridge, and construction of campgrounds.

The spring, summer, fall, and winter range of the remnant population has been defined by a 4-year radio-tracking study. Only one active strutting ground was found in the valley. Surveys found no evidence of birds living in areas previously supporting sage grouse. These areas were Trout Creek, Chicken Creek (west and east), Co-op Creek, Strawberry River, and Mosquito Bay.

A recovery plan is presented. The plan consists of protecting and rejuvenating the big sagebrush resources, defining critical sage grouse habitat, setting aside areas as priority sage grouse habitat or areas to be rejuvenated, constructing watering holes, creating surrogate strutting grounds near Road Hollow, and transplanting birds to unoccupied habitat.

Sage Grouse Status and Recovery Plan for Strawberry Valley, Utah

Bruce L. Welch
Fred J. Wagstaff
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INTRODUCTION

The decline of sage grouse (*Centrocercus urophasianus*) in the Strawberry Valley resulted mainly from managing the area for maximum productivity of a single range use, livestock production. History of Strawberry Valley showed sizable adverse effects from converting public rangelands from shrublands to grasslands. In our view increased livestock productivity did not justify this conversion.

In October 1989, the lands in question came under the administrative control of the U.S. Department of Agriculture, Forest Service, Uinta National Forest, Heber District. One of the goals of the new managers is to restore sage grouse habitat in the Strawberry Valley. This report serves as the foundation for the recovery plan. The report draws heavily on a study of sage grouse numbers and distribution conducted by the Intermountain Research Station and the Heber District from 1986 through 1989.

This report covers the biology of sage grouse, the impacts of past management of the Strawberry Valley on sage grouse, past and current range and numbers of birds, critical use areas, and recovery recommendations. The report proposes formation of a Strawberry Valley sage grouse recovery team.

BIOLOGY OF SAGE GROUSE

Sage grouse (spiny-tailed pheasant), often known locally as sage hen or chicken, are the largest of the native United States grouse. Mature males average about 6 pounds but can weigh as much as 7 pounds. Females weigh about half as much as the males. The sage grouse has been described as the chief ornament of the North American fauna (Patterson 1952). The annual mating dance of the males is spectacular. The sage grouse was discovered by Lewis and Clark above the head waters of the Missouri River, and on the plains of the Columbia River. The explorers named it the "cock of the plains" (Rasmussen and Griner 1938).

No other North American game bird is so inextricably dependent upon one plant species as sage grouse is on big sagebrush (*Artemisia tridentata*) and its near relatives (Roberson 1984). Rasmussen and Griner (1938) observed close agreement between the original range of sage grouse and the distribution of big sagebrush and its near relatives (also compare Beetle's [1960] distribution map of big sagebrush with Patterson's 1952 sage grouse range map). Patterson (1952) observed that the birds showed no signs of adjusting to the eradication of big sagebrush (also see Braun and others 1977). Sage grouse use sagebrush for food, escape, roosting, loafing, brooding, and nesting cover. They are seldom found far from these plants (Peterson 1970a). Sage grouse have a near-obligate relationship with big sagebrush and its close relatives of the subgenus *Tridentatae* of *Artemisia* (Roberson 1984).

The dependence of sage grouse on big sagebrush is illustrated by the food preferences of the bird. Sage grouse lack a muscular gizzard containing grit and thus cannot digest hard foods such as seeds. They depend on soft foods (Autenrieth 1986; Braun and others 1977; Patterson 1952). From October to April, big sagebrush leaves and short shoots make up from 90 to 100 percent of the diet of sage grouse (Braun and others 1977; Patterson 1952; Roberson 1984; Wallestad and others 1975). For 7 out of 12 months, or 58 percent of the year, sage grouse eat nearly pure diets of big sagebrush.

Even in spring and summer when other foods are available, adult sage grouse still consume large quantities of big sagebrush. Patterson (1952) reported that, in a Wyoming study, it was only during the summer that big sagebrush made up less than 80 percent of the diet of sage grouse. He found that big sagebrush comprised 87 percent of the spring diet and 45 percent of the summer diet of adult sage grouse. Rasmussen and Griner (1938) found that big sagebrush and silver sagebrush (*A. cana*) comprised 88 percent of the spring diet and 49 percent of summer diet of adult sage grouse in the Strawberry Valley of Utah. In Montana, Martin (1970) found that big sagebrush made up 34 percent of the summer diet of adult sage grouse. Also in Montana, Wallestad and others (1975) reported that big sagebrush comprised 84 percent of the spring diet and 8 percent of the summer diet of adult sage grouse.

In Idaho, Gates and Eng (1983) found that big sagebrush comprised 77 percent of the spring/summer diet of adult sage grouse. Leach and Hensley (1954) and Leach and Browning (1958) found that the late summer diet of California sage grouse was 42 percent big sagebrush. It appears that year-round use of big sagebrush by adult sage grouse reaches a low of about 43 percent during the summer, increases to 86 percent in the spring, and reaches a high of 92 percent for the fall/winter season.

The diet of young sage grouse differs from that of adults. Rasmussen and Griner (1938) studied the food habits of juvenile sage grouse in the Strawberry Valley of Utah. They found that big sagebrush and silver sagebrush made up 25 percent of the June diet, 22 percent of the July diet, and 36 percent of the August diet. After August, the diet of juvenile sage grouse was similar to that of adults. Insects and forbs were extremely important in the June, July, and August diets of juvenile sage grouse. Similar results were reported by Patterson (1952) in Wyoming, Klebenow and Gray (1968) in Idaho, and Peterson (1970b) in Montana.

The importance of sagebrush in the life history of sage grouse is further illustrated in the bird's preference for cover and the selection of nesting sites. Sage grouse hens nest almost exclusively under big sagebrush plants. Researchers found that 90 to 95 percent of the nests were placed under big sagebrush plants (Roberson 1984). Hens appear to select nesting sites beneath big sagebrush that has a good canopy cover and is relatively tall. Autenrieth (1981) observed that big sagebrush plants with an umbrella effect were usually selected by the hen. He attributed this selection to improved survival of the hen and improved nest success due to protective camouflaging. "The importance of big sagebrush cover for nesting cannot be overestimated" (Autenrieth 1981).

Most studies indicate that the majority of nests are located under the tallest plants available in an area (Roberson 1984). One study showed that hens preferred big sagebrush to black sagebrush for nesting (Roberson 1984). Autenrieth (1981), however, found that hens selected something less than the tallest and densest canopy cover. He believed that the height and density of sagebrush on his study area was greater than those in other studies. Apparently height and density of canopy cover were not limiting factors in the Autenrieth (1981) study. Average height of nesting plants ranged from about 16 to 31 inches. Canopy cover (percentage of the ground covered by big sagebrush) for nesting sites ranged from 20 to 40 percent (Roberson 1984).

The quantity and quality of big sagebrush is important even on the mating grounds. Characteristics of strutting grounds vary greatly. They may be bare openings in big sagebrush, gravel pits, plowed fields, wheat stubble, salt licks, remote air strips, temporary sheep camps, paved roads, bare exposed ridges, knolls, small buttes, and dry lake beds (Roberson 1984). Strutting grounds are not distinctive except that they are surrounded by big sagebrush cover. Sagebrush plants surrounding the strutting grounds are of critical importance. These plants are used as escape cover for females coming into the strutting ground. They provide food and loafing areas for the males. The height and canopy cover values for nesting sites are similar to the characteristics of loafing sites selected by males near strutting grounds.

In summary, sage grouse depend on big sagebrush and associated forbs and insects to fulfill their basic requirements. The future of sage grouse, in the Strawberry Valley and elsewhere, depends on our ability and willingness to maintain suitable sagebrush habitat types. Big and silver sagebrush populations are recovering throughout the entire valley. Some areas are more advanced than others but the sagebrush in general is coming back. The status of forbs needs to measured.

IMPACT OF PAST MANAGEMENT OF THE STRAWBERRY VALLEY ON SAGE GROUSE

The Strawberry Valley is a high (8,000-foot) mountain valley comprising some 175 to 188 square miles (see fig. 1 for boundary details). The valley is located in north-central Utah about 20 miles southeast of Heber City, UT. The valley is a mixture of public lands managed by the Heber Ranger District, private lands, and lands owned by the Uintah and Ouray Indian tribes. Strawberry Reservoir is the dominant feature of the valley.

In the early 1900's, several thousand acres of the Strawberry Valley were withdrawn from public lands by the Bureau of Reclamation. The Bureau constructed a dam that formed the Strawberry Reservoir. Lands not inundated by the reservoir came under the management of a private organization called the Strawberry Valley Water Users Association even though the public ownership continued. The association managed the lands of the reclamation withdrawal for cattle and sheep production.

Rasmussen and Griner (1938) estimated in 1936-37 that the valley supported 3,000 to 4,000 sage grouse. They also reported the establishment of a Federal refuge to aid sage grouse and migratory waterfowl. Sometime in the past the refuge was abolished. Smith and Greenwood (1983) reported that in the early 1980's the sage grouse population was 250 to 350 birds. This represents a 90 percent

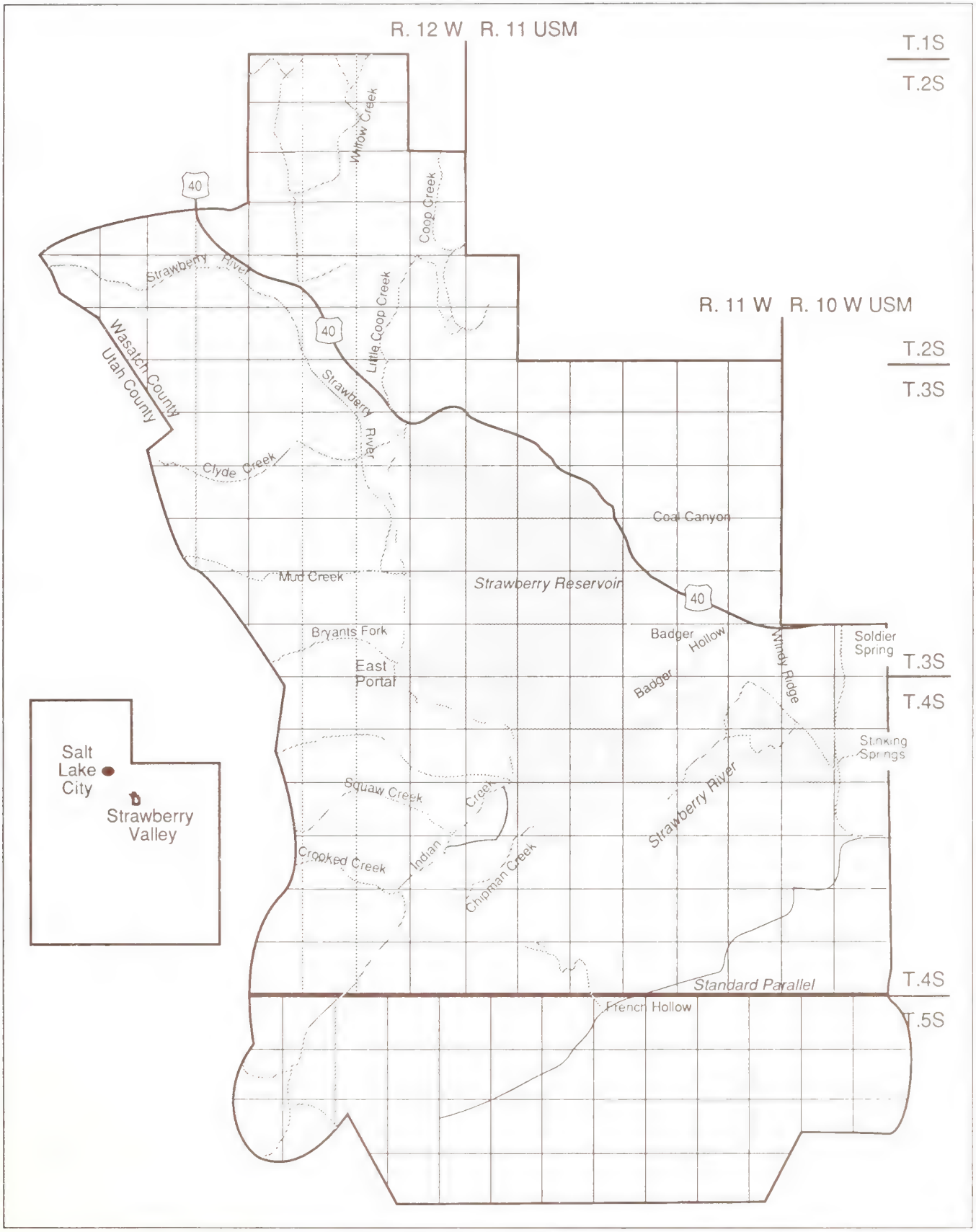

Figure 1—Location map, Strawberry Valley of north-central Utah (Uinta Special Meridian).

decline in population size since the 1930's. The decline was due to the eradication of big sagebrush and silver sagebrush to maximize grass production. The herbicides used destroyed not only the big and silver sagebrush needed by adult birds but also the forbs needed by chicks. The importance of forbs in the diet of chicks has been documented by a number of researchers (Braun and others 1977; Call 1979; Connelly and Ball 1983; Crawford and Lutz 1985; Grandison and Welch 1987; Klebenow 1970, 1982; Martin 1970; Patterson 1952; Peterson 1970a, 1970b; Roberson 1984; Swensow and others 1987; Wallestad and Pyrah 1974). Past management of the Strawberry Valley is a classic example of single-use management failing to consider and provide for other range uses. A visible example of rangeland deterioration in this valley is the near extermination of willow (*Salix* spp.). Willows are very important in stabilizing the riparian ecosystem. Griner (1939) estimated that the valley contained 770 acres of willow. Now there is less than 10 acres.

CURRENT RANGE OF SAGE GROUSE

Starting in April of 1986, we collected, by means of a rocket net, female sage grouse from the Road

Figure 2—Spring/summer/fall range of sage grouse in the Strawberry Valley. Areas outlined in dark lines and numbered are heavy sage grouse use areas (Uinta Special Meridian).

Table 1—Spring/summer/fall movement of radio-marked sage grouse among the seven areas defined in figure 2. Numbers in columns under the various areas are individual radio-marked hens (except 933, which was a male). Hens returning from a previous year are designated by the letters RB (return of bird from last year). Reuse of an old radio is noted by the designation NH meaning (old radio, new hen)

Year	Areas							
	1	2	3	4	5	6	7	Outside[1]
1986	127 250	167	49 370	182 328			85 208	49 85 250
1987	49RB		167RB 182NH	835	328NH 581		85RB 351	12 370NH
1988	813 982 1.012	835NH	167RB 208NH 407	912	864	892 933		1.012
1989	892RB 1.012RB		407RB 813RB	912RB	864RB		982RB	407RB

[1]Details of bird location given in the text for the year specified

Hollow strutting grounds (fig. 2). We fitted captured hens with solar-powered radio transmitters attached to bibs. Only data from those hens that carried a functional transmitter into October were used (many went beyond this period). Table 1 shows the number of birds for each year of the study. Readers should note that for the years 1987, 1988, and 1989 some of the birds returned from the previous year with functioning transmitters. Contact was made once a month with the radio-marked hens on their spring, summer, and fall range. In August we noted the number and location of nonmarked hens flushed during our search for radio-marked hens. We attempted to locate the birds once a month on their winter range.

After the 1987 data-collecting season, we noted that on the spring, summer, and fall range a large majority of the birds were using seven areas for nesting and brood rearing. One of the seven areas was also a loafing area for the males. Areas are outlined in figure 2. Movements of hens and one male from the Road Hollow strutting grounds are summarized in table 1. Details not given in table 1 are given below.

Bird Movement—1986 Spring/Summer/Fall

Radio frequencies (150.000 mhz) for the nine hens were 49, 85, 127, 167, 182, 208, 250, 328, and 370. (Hen 167 was captured in area 2 and fitted with a radio in October 1985). Hen 49 nested just east of area 3. After her five chicks hatched she moved them into area 3. There they stayed until they left for their winter range. Hen 85 was found east of area 7 during June and July and then spent the remainder of the summer and fall in area 7. The remaining hens spent the spring/summer/fall in the areas indicated in table 1.

During the August contact period, we noted the number and location of nonmarked hens and males we flushed during our search for radio-marked hens. We found 16 hens in area 1, 13 hens in area 2, three hens in area 3, five hens in area 4, five hens in area 5, 26 males in area 6, and five hens in area 7.

Bird Movement—1987 Spring/Summer/Fall

Radio frequencies for the 10 hens were 12, 49 (return from 1986), 85 (return from 1986), 167 (return from 1986), 128 (old radio, new hen), 328 (old radio, new hen), 351, 370 (old radio, new hen), 581, and 835. All but two hens remained in one of the seven areas during the spring/summer/fall period. Bird 370 nested and raised her five chicks about one-half mile west of area 2. Bird 12 spent the spring/summer/fall period about three-fourths mile west of area 1. The remaining hens spent the spring/summer/fall in the areas indicated in table 1.

During the August contact period, we noted the number and location of nonmarked hens and males we flushed during our search for radio-marked hens. We flushed 17 hens in area 1, 10 hens in area 2, eight hens in area 3, five hens in area 4, six hens in area 5, two hens and 21 males in area 6, three hens in area 7, three hens between areas 1 and 6, and three hens between areas 2 and 3.

Bird Movement—1988 Spring/ Summer/Fall

Radio frequencies for the 10 hens and one male were 167 (return from 1986 and 1987), 208 (old radio, new hen), 407, 813, 835 (old radio, new hen), 864, 892, 912, 933 (male), 982, and 1.012. All hens were found in one of the seven areas except one (table 1). Hen 1.012 spent June and July in area 1 but moved between areas 1 and 6 for the remainder of the spring/summer/fall period. Unlike the other years, we noted movement from area to area for two hens. Hen 813 started in area 3 in June and moved to area 1 for the remainder of the spring/summer/ fall period. Hen 892 moved from area 1 in August to area 6 for the reminder of the spring/summer/fall period.

During the August contact period, we noted the number and location of nonmarked hens and males that we flushed during our search for radio-marked hens and the male. We flushed eight hens in area 1, two hens in area 2, three hens in area 3, three hens in area 4, four hens in area 5, three hens and 18 males in area 6, three hens in area 7, and three hens between areas 2 and 3.

Bird Movement—1989 Spring/ Summer/Fall

Radio frequencies for the seven hens were 407, 813, 864, 892, 912, 982, and 1.012. All of these hens were return birds from 1988. All hens were found in one of the seven areas except one (table 1). Hen 407 was found between areas 2 and 3 in July. In the other months she was located in area 3.

During the August contact period, we noted the number and location of nonmarked hens we flushed during our search for radio-marked hens. We flushed 10 hens in area 1, no hens or males in area 2, three hens in area 3, seven hens in area 4, four hens in area 5, 10 hens and 19 males in area 6, and two hens in area 7.

Observations of Bird Movement on Spring/Summer/Fall Range

Pooling the radio-marked hens and the single male observations over the 4 years yields a ranking of the seven nesting and brooding areas (table 2). Twenty-four percent of the observations were in area 3; 19 percent in area 1; 14 percent in area 4;

Table 2—Seasonal distribution of marked and nonmarked sage grouse in areas defined in figure 2. Data are expressed as number of female birds found in the area. Nonmarked birds were also hens found in the areas during August of each year[1]

	Areas								
Item	1	2	3	4	5	6	7	Outside	Total
Marked birds									
1986	2	1	2	2	0	0	1	1	9
1987	1	0	2	1	2	0	2	2	10
1988	2	1	3	1	1	2	0	1	11
1989	2	0	2	1	1	0	1	0	7
Total	7	2	9	5	4	2	4	4	37
Percent	19	5	24	14	11	5	11	11	
Nonmarked birds									
1986	16	13	3	5	5	0	5	0	47
1987	17	10	8	5	6	2	3	6	57
1988	8	2	3	3	4	3	3	3	29
1989	10	0	3	7	4	10	2	0	36
Total	51	25	17	20	19	15	13	9	169
Percent	31	15	10	12	11	9	8	5	

[1]Male sage grouse were found during August only in area 6 (26 in 1986, 21 in 1987, 18 in 1988 and 19 in 1989).

11 percent each in areas 5, 7, and outside the seven areas; and 5 percent each in areas 2 and 6. Results of counts made for the nonmarked hens are also given in table 2.

Area 2 is of special interest. This area is located in a summer home development on Windy Ridge. Smith and Greenwood (1983) have described this area as the best brooding habitat in the Strawberry Valley. In the fall of 1985, it was common to see sage grouse along roads, around the summer homes, and in the big and silver sagebrush. After the spring of 1987, the number of birds sighted fell (table 2). This corresponds very closely with the movement of bird 167 out of area 1 to area 3 (1987 and 1988). Table 2 shows a dramatic drop in the number of nonmarked birds from 1986 to 1989. We not only searched the area during the normal time in August 1989 but also searched the area again in October 1989 (unlike other areas we conducted equal searches in area 2 for the 4 years). Both searches flushed no birds. This corresponds to flushing an average of 11 birds during 1986 and 1987. Talks with seven home owners supported our conclusions. They reported seeing substantially fewer birds during the last 2 years. We believe that the birds are abandoning this area, probably because of increased home building, increased human activities, increased removal of big and silver sagebrush plants, and perhaps drought.

Winter Range

Usually most sage grouse in the Strawberry Valley leave for their winter range around mid-November. The timing of this annual movement appeared to be independent of the depth of snow. Movement out of the Valley is eastward, with a slight increase in elevation.

We have located eight wintering areas. These areas are delineated in figure 3. Perimeters of areas circumscribed all sites where marked and nonmarked birds, droppings, tracks, and feathers

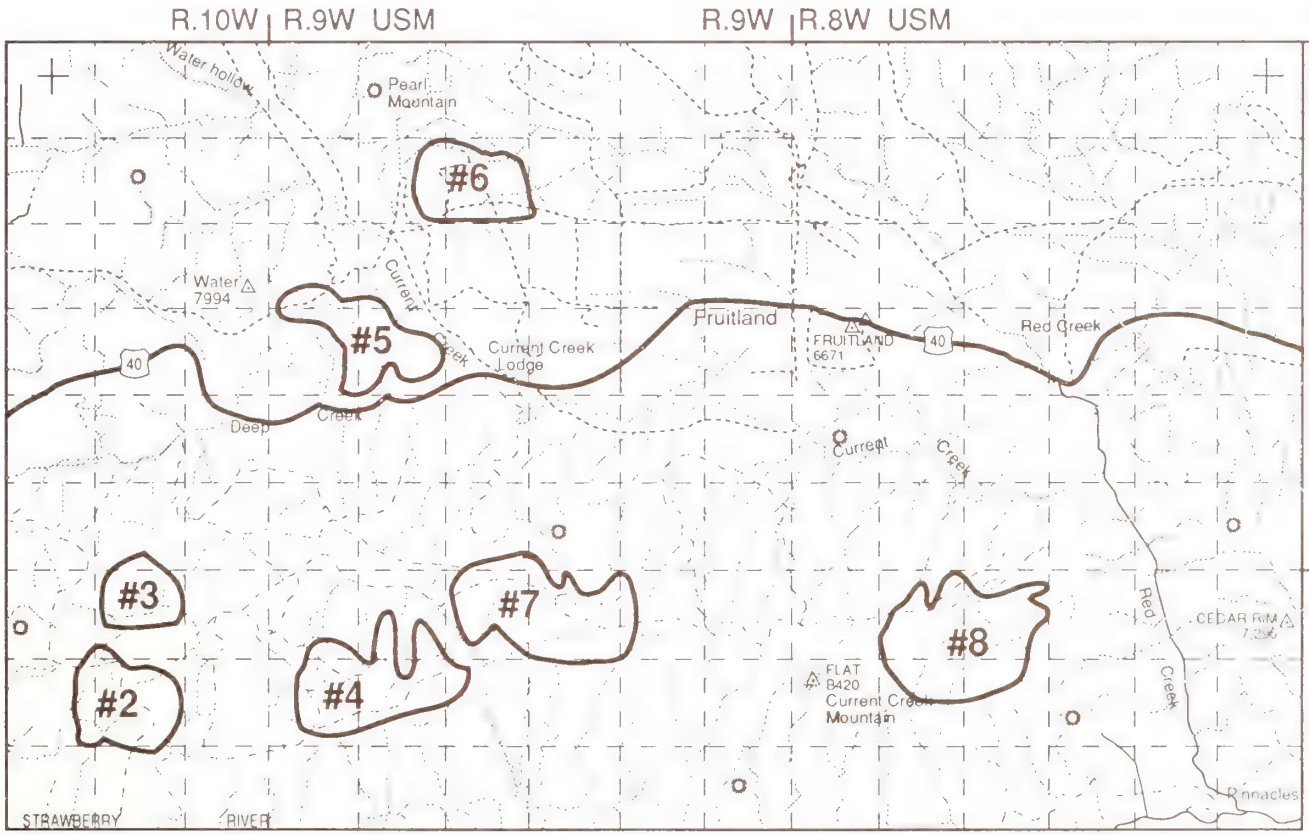

Figure 3—Winter range of sage grouse of the Strawberry Valley. Numbered areas outlined in dark lines and numbered are heavy sage grouse use areas (Uinta Special Meridian).

were found. The birds were distributed over a large area. They did not express the same fidelity for winter range that they did for their spring/summer/fall range. Most of the winter range is under private ownership, except area 6, which is under the ownership of the Bandanna Ranch (a sport group) and the Utah Division of Wildlife Resources.

Area 1 is found in the Chipman Creek areas next to area 4 of the spring/summer/fall range (fig. 2). This is the only known wintering area in the Strawberry Valley. We found hen 328 wintering (1986-87) in this area with 15 other hens. These birds remained in the area until breeding time in early April. In 1988-89, hen 1.012 was found wintering in this area with six other hens. The hens left the area for area 7 in late February when deep snow completely covered all the big sagebrush plants.

Area 2 is located at the head of Pine Hollow (fig. 3). Hen 250 wintered here with 23 other birds (1985-86). We found 29 nonmarked birds wintering here in 1986-87, and 12 nonmarked birds in 1988-89 until snow depth covered the big sagebrush plants in late February.

Area 3 is located just north of area 2 (fig. 3). We found seven nonmarked birds wintering in this area in 1985-86. No birds where found in this area for the next three winters.

Area 4 is located about 1½ miles east of area 2 or just east of the head of Bear Hollow. Hen 289 was found in this area in 1986-87. This was a radio-marked hen we did not locate on the spring/summer/fall range but found on the winter range. Seven nonmarked birds also wintered here during this winter. In the winter of 1988-89, another hen, 813, was located in this area with 17 nonmarked birds.

Area 5 is located about 3 miles north of area 4 across U.S. Highway 40 just west of U.S. Highway 40 junction with the Current Creek Road. Hen 85 was found wintering in this area (1986-87) with 17 nonmarked birds. We found five nonmarked birds in this area during the winter of 1988-89.

Area 6 is located about 2¾ miles north of the Current Creek Store (fig. 3). Two hens, 49 and 127, were found wintering in this area during the winter of 1986-87 with 35 nonmarked birds. We did not find any birds wintering in this area during the winter of 1988-89. This was surprising in light of the large numbers of birds there during the winter of 1986-87. This observation supports our belief that wintering birds may not express the degree of fidelity for winter range that they do for spring/summer/fall range.

Area 7 is located about 2 miles south of the Current Creek Store (fig. 3). During the 1988-89 winter, we found three hens—892, 912, and for February and March, 1.012. We further found 86 nonmarked birds wintering in this area. We found no birds in this area during the winters of 1985-86, 1986-87, and 1987-88. Again, apparently birds do not have the strong preference for winter range that they do for spring/summer/fall range.

Winter range does not appear to be a limiting factor in the production of sage grouse in the Strawberry Valley Area. This opinion is based on two supporting observations: first, the birds seem to disperse over a vast area and lack the fidelity for a particular area; second, the wintering areas support adequate stands of big sagebrush. The wintering areas are dissected by deep drainages; therefore, herbicidal removal of big sagebrush would not be economically feasible.

NUMBERS OF BIRDS

The hardest part of this study was determining just how many birds are in the Strawberry Valley. Based on strutting ground counts we place the total population at 160 to 185 birds. This value is based on peak male counts on the Road Hollow strutting ground in 1988 and 1989. Peak count for 1988 was 30 and for 1989, 26. The peak male count is multiplied by 2 (the ratio between females and males), the number of females is then multiplied by 40 percent (nest success), and the result multiplied by the average number of brood size (3.98) (Smith and Greenwood 1983). These values are down from the estimates of 250 to 350 birds reported by Smith and Greenwood (1983), which were down drastically from the estimates of Rasmussen and Griner (1938) (3,000 to 4,000 birds). Since the Smith and Greenwood (1983) estimates of bird numbers, the Stinking Springs strutting grounds with its associated nesting and brooding areas has been lost to reservoir enlargement. This probably accounts for the drop in numbers of birds from Smith and Greenwood's (1983) estimate to ours.

PAST RANGE OF SAGE GROUSE

Smith and Greenwood (1983) reported the existence of five strutting grounds in the Strawberry Valley. These strutting grounds were located at Stinking Springs (Green Knoll), Trout Creek, Trail Hollow, Co-op Creek, and Road Hollow. We searched these areas in late April 1989 and found no active strutting grounds except in the Road Hollow area. Stinking Springs (Green Knoll) strutting ground has been flooded by the new Strawberry Reservoir. This means that sage grouse have suffered an 80 percent reduction in number of strutting grounds in Strawberry Valley. This may explain why we found only a fraction of the number of birds reported by Rasmussen and Griner (1938).

In addition to searching for strutting grounds, we also searched other areas of the valley for possible sightings and signs of sage grouse. During July of 1989, we searched the following areas for sage grouse and signs of sage grouse: the area south of U.S. Highway 40 below Trout Creek (15 miles of transect), the area north of U.S. Highway 40 at Trout Creek (14 miles of transect), the area north of U.S. Highway 40 at Chicken and Co-op Creeks (36 miles of transect), the Strawberry River starting at the visitor center and ending at U.S. Highway 40 (54 miles of transect), and the area south of U.S. Highway 40 starting at the Strawberry River and ending on the east side of Jake's Bay (8 miles of transect). Our search was conducted on horseback and on small all-terrain vehicles. We covered about 127 miles in the search areas. Our search of 127 miles did not locate any birds or signs of birds. Birds are absent from former locations. The apparent cause of the decline was habitat destruction caused by large spraying operations to eradicate sagebrush. Other activities such as building of roads, campgrounds, and summer homes, reservoir enlargement, and associated increases in human traffic certainly contributed to the decline of sage grouse in the Strawberry Valley. To sum up, the few remaining birds of a once large and widespread population survive only at the Road Hollow strutting ground and its associated nesting, brooding, and loafing sites. This area was described by Smith and Greenwood (1983) as critical sage grouse habitat.

RECOMMENDATIONS

We offer the following recommendations as a start in developing and implementing a recovery plan:

1. Careful consideration of sage grouse needs before conducting sagebrush control projects.
2. Adherence to the "Guidelines for Maintenance of Sage Grouse Habitats" (Braun and others 1977).
3. Including in the forest plan provisions for the management of critical sage grouse habitat encompassing the following sections; 26, 25, 34, 35, 36 of range 11 west (Uinta Special Meridian), township 3 south; 1, 2, 3, 9, 10, 11, 12 of range 11 west (Uinta Special Meridian), township 4 south; and 20, 21, 28, 29, 30, 31, 32, 33 of range 11 west (Uinta Special Meridian), township 4 south.
4. Construction of water developments for sage grouse use on section 12 of range 11 west (Uinta Special Meridian), township 4 south.
5. Creating three alternative strutting grounds in section 2 of range 11 west (Uinta Special Meridian), township 4 south. (The present strutting grounds will be flooded when the enlarged reservoir is filled.)
6. Rejuvenating the forb and sagebrush component, wet meadows, springs, and seeps of the Trout Creek area. When the habitat is suitable, cooperate with the Utah Division of Wildlife Resources in the creation of a strutting ground and in transplanting of sage grouse to the area. Identify in plans and maps the Trout Creek area as priority sage grouse habitat. This area includes the following sections: 3, 4, 8, 10, 15, 16 of range 11 west (Uinta Special Meridian), township 3 south.
7. Rejuvenating the forb and sagebrush components, wet meadows, springs, and seeps of the Chicken and Co-op Creek area. When the habitat is suitable, cooperate with the Utah Division of Wildlife Resources in the creation of a strutting ground and the transplanting of sage grouse to the area. Identify in plans and maps part of the Chicken and Co-op Creek area as priority sage grouse habitat. This area includes the following sections: 5, 6, 7, 8 of range 11 west, township 3 south; 29, 30, 31, 32 range 11 west, township 2 south.
8. Supporting research to determine the effects of grazing cattle and sheep on nesting sage grouse and broods. We believe that the actual grazing of cattle in sage grouse habitat, after nesting, probably has little effect on sage grouse. It is the destruction of sagebrush stands and forbs to increase grass production that has the most harmful effects on sage grouse. Sheep that tend to graze in more dense groups, may have a more negative effect on sage grouse. Research is needed to measure these effects.
9. Forming a Strawberry Valley sage grouse recovery team to formulate goals and implement plans for habit improvement and increasing sage grouse populations. The goal of the recovery team would be to increase the number of birds to 1,000 by the year 2000. Membership of the team should include at least one representative each from the Heber Ranger District, Utah Division of Wildlife Resources (CRO), Intermountain Research Station, private nonprofit conservation organizations, and other interested parties. The charge of the team would be to develop a plan to implement the recommendations of this report, to obtain support and resources to conduct and supervise the habitat improvement projects, to transplant sage grouse into the Trout Creek, Chicken, and Co-op Creek areas, to monitor the success of the transplanting program, and to conduct research on the interactions of sage grouse and livestock grazing. The team would also develop guidelines concerning the management of critical and priority sage grouse habitat.

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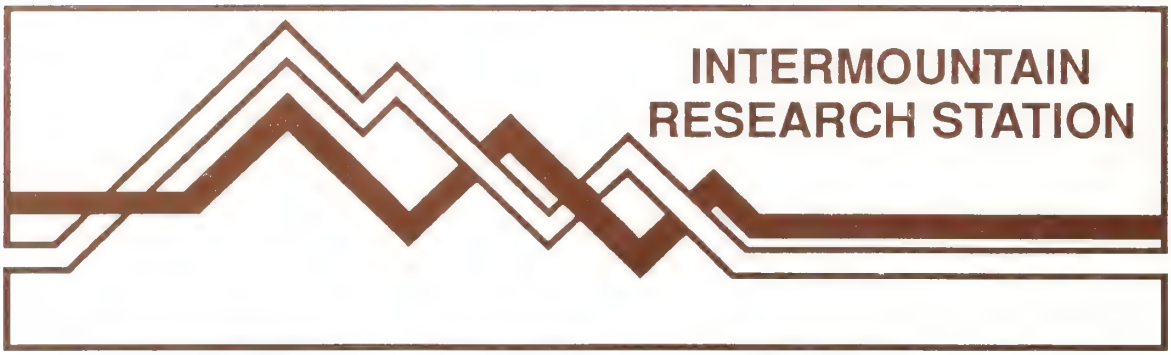
Since 1939, an estimated 3,000 sage grouse in Strawberry Valley, UT, have declined to some 180 birds, mainly because of reservoir construction and eradication of big sagebrush to promote livestock forage. A 4-year study of numbers and movements of radio-tagged grouse has provided the basis for a recovery program calling for rejuvenation of big sagebrush and forbs important to grouse, replacement of mating grounds lost to human activities, consideration of sage grouse biology in management decisions, and formation of a sage grouse recovery team.

KEYWORDS: wildlife management, radio tagging, sage grouse management, sagebrush rejuvenation



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